Abstract

Background:

Although there is evidence that stroke survivors have reduced gait adaptability, the underlying mechanisms and the relationship to functional recovery are largely unknown. We explored the relationships between walking adaptability and clinical measures of balance, motor recovery and functional ability in stroke survivors.

Methods:

Stroke survivors (n=42) stepped to targets, on a 6m walkway, placed to elicit step lengthening, shortening and narrowing. The number of targets missed during six walks (3 targeting with paretic limb and 3 with non-paretic) and target stepping speed was recorded. Fugl-Meyer scores (FM), Berg Balance Scale (BBS), self-selected walking speed (SWWS) and single support (SS) and step length (SL) symmetry (using GaitRite when not walking to targets) were also assessed. Stepwise multiple-linear regression was used to model the relationships between: total targets missed, number missed with paretic and non-paretic legs, target stepping speed, and each clinical measure.

Results:

Regression revealed a significant model for each outcome variable that included only one independent variable. Targets missed by the paretic limb, was a significant predictor of FM($F_{(1,40)}$=6.54, p=0.014,). Speed of target stepping was a significant predictor of each of BBS($F_{(1,40)}$=26.36, p<0.0001), SSWS($F_{(1,40)}$=37.00, p<0.0001) and SS asymmetry ($F_{(1,38)}$=5.57, p=.006). No variables were significant predictors of SL asymmetry.

Discussion:

Speed of target stepping was significantly predictive of SS symmetry, BBS and SSWS and paretic targets missed predicted FM, suggesting that fast target stepping requires good balance and temporal symmetry of gait and accurate stepping demands good paretic leg function. The relationships between these parameters indicate gait adaptability is a clinically meaningful target for measurement and treatment of functionally adaptive walking ability in stroke survivors.

Keywords: gait, adaptability, stroke, vision

Background:

The ability to adjust the on-going walking pattern in response to environmental and task goals is key to regaining independent mobility in the community following stroke. However, reports indicate few stroke survivors can independently climb stairs and inclines, and walk the speeds and distances required for mobility in the community [1, 2]. Further reports indicate that after a stroke most falls are caused by trips, slips, or misplaced steps while walking [3, 4]. This suggests that an inability to adapt the walking pattern in response to the environment may be a key factor limiting recovery of independent mobility in stroke survivors. Indeed, there is strong evidence to indicate that stroke survivors have reduced gait adaptability; indicated by impairments in obstacle avoidance (e.g.[5, 6]), turning (e.g.[7-9]) and in initiating and executing step adjustments (particularly to place the foot medially) in response to external cues [10, 11]. However, the relationships between poor gait adaptability and functional recovery/mobility are still largely unknown.

Adaptability of gait has been defined as: “the ability to adjust gait to environmental circumstances, such as obstacles and targets” (pg 1453 [12]). However, in line with dynamic systems theories of what constitutes stable movement patterns [13], it could be argued that this definition of adaptability should also include the stipulations that adjustments to gait be achievable while maintaining forward progression and postural equilibrium. A recent review [14] described adaptability as part of a tri-parte model of walking (including adaptability, stepping and stability). This multifaceted nature of adaptability may be a key reason why it is difficult to measure. Many clinical measures aimed at capturing aspects of adaptability (e.g. Timed Up and Go, Dynamic Gait Index, Modified 10m walk test) quantify overall success of and time taken to perform, rather than how the adaptations are achieved[14].

Biomechanical analyses of how locomotor adaptations such as obstacle avoidance, turning and target stepping paradigms are achieved have however suggested that impaired ability to alter foot-placement in order to target a specific footfall location may underlie impaired adaptability [5,6,10,15]. For example, individuals with stroke have shown inaccurate foot placement of the affected lead foot when clearing obstacles [5, 15]. Further, stroke survivors have been shown to have difficulties making medial-lateral step corrections [10] and deficits in adjusting foot-placement are exacerbated under time pressure [5, 6, 10]. In healthy older and younger adults target stepping paradigms to test the ability to adapt and control footplacement have shown discriminatory power for age and been associated with falls risk and cognitive function [16-20]. Control and adaptability of footfall location may therefore be a mechanistic component facilitating overall gait adaptability; especially given that foot placement adjustments are one of the most effective mechanisms for dynamic balance control during walking [10] and many falls have been reported due to misplaced step[4].

The aims of this study were to measure the ability of stroke survivors to adapt their gait in order to step on irregularly spaced targets and to assess the strength of the relationship between this measure of adaptability and clinically valid measures of balance and motor recovery.

Understanding the relationships between the ability of stroke survivors to adjust foot-placement and clinically relevant measures of balance, functional mobility and motor recovery will offer insight into whether or not adaptability of walking is relevant to functional recovery. Further, exploration of the relationships between adaptability and recovery may provide insights into the mechanisms that might underpin altered gait adaptability in stroke patients. For example, if target stepping performance correlated highly with Berg Balance Scale scores but not self-selected walking speed then this would suggest that the mechanism underlying poor gait adaptability is compromised balance rather than walking ability

Methods:

Participants were people taking part in a larger clinical trial [21]. Community dwelling adult stroke survivors were identified either at discharge from inpatient stroke services or at referral to community and outpatient services at six hospitals across the West-Midlands in the UK. Participants were included if they:

1) had a gait impairment (speed <0.8m/s corresponding with limited community ambulation ability [22] and residual lower limb paresis (Fugl-Meyer [23] lower limb score <34) due to their stroke (premorbid (retrospective) modified Rankin Scale [24] score >3)

2) were able to walk with minimal assistance (functional ambulation category [25] of 3 or more)

3) were able to follow a three-step command (as assessed by Modified Mini-mental Status Exam [26]) and able to give informed consent.

4) had no severe visual impairments that would prevent sight of stepping targets.

Potentially eligible participants were excluded if:

1) mobility limitations were attributable to non-stroke pathology and/or they had a co-morbidity preventing mobilization or

2) they required palliative care.

The study was approved by the National Research Ethics Committee- West Midlands and all participants provided informed written consent.

As part of the baseline assessment within the larger clinical trial participants underwent the Berg Balance Scale assessment, the Fugl-Meyer lower limb assessment, a spatio-temporal analysis of their unconstrained over-ground walking pattern (using GaitRite) and a target stepping task of gait adaptability.

The target stepping task required participants to step to targets eliciting step length adjustments of (8cm deep x 40cm wide x1mm thick) adhered to a 6m walkway (see Figure 1). The depth of the targets corresponds to the variability in step length reported in stroke patients [27]. The width of step-length targets corresponds to half the width of the walkway, such that step-width is not constrained simultaneously while participants are required to make adjustments to step length. Targets eliciting step width adjustments (20cm deep x 15cm wide) were located on the midline of the walkway at the usual step length for each limb (so that lengthening/shortening was not also required while narrowing).

The location of cues was calculated for each patient based on the average paretic and non-paretic step lengths measured when walking (without targets) over a 3m pressure-sensitive mat (GaitRite). Based on each patients' usual gait pattern, targets were placed to elicit step adjustments i.e. lengthening, shortening (±25% of usual step lengths) and narrowing of paretic and non-paretic steps. The choice to use 25% adaptations to step length was pragmatic – with participants in study design phases indicating this was sufficiently challenging without causing them to feel unsafe or the task being unachievable. Targets were arranged as depicted in Figure 1.

Instructions were to walk as quickly and as safely as possible over the walkway whilst stepping on the targets with any part of the foot. Thus, a target was recorded as missed if the participant was visually observed to be unable to place any part of the foot on the target.

INSERT FIGURE 1: METHODS SCHEMATIC

The number of targets missed in six consecutive passes (3 in each of the outbound and return directions) of the walkway (a total of 48 targets including three attempts of each step adjustment on each leg) as well as time taken to complete each pass of the walkway, using a stopwatch, was recorded. Speed of target stepping was derived from this measure and calculated as 6 (length of walkway in m) / time taken to complete target task (s).

Previous studies have indicated that difficulty in controlling placement of the lead limb during obstacle avoidance may be due to impaired muscle activation/motor function [6]. Further, controlling footplacement is a mechanism for maintaining balance during walking [10]. Therefore, we sought to explore the relationship between adaptability, as measured by our target stepping paradigm, and established clinical measures of motor recovery (Fugl-Meyer lower limb assessment (FM)[23] balance (Berg Balance Scale (BBS) [28] as well as overall walking competence (self-selected walking speed (SWWS)[22] (using GaitRite)). All measures were taken at baseline (i.e. prior to randomization into walking rehabilitation treatments) within the clinical trial in which participants were enrolled.

Adapting footfall locations in response to environmental demands may be particularly challenging for stroke patients due to the fact that the task imposes step asymmetries on an already asymmetric walking pattern. So we also sought to explore the relationship between the ability to alter footfall location and asymmetry of single support time and step length. Symmetry ratios were calculated by dividing the larger of the paretic or non-paretic value (step length or single support time) by the smaller; in accordance with recommendations [29]. Thus a value of 1 represents symmetrical gait and >1 is increasingly asymmetrical.

Total targets missed as well as number missed on the paretic and non-paretic sides and speed (calculated using the mean speed from 6 passes of the walkway) were regressed, using stepwise multiple linear regression (SPSS v 20.0), onto each of the symmetry ratios, BBS, FM and SSWS.

***Results*:**

Participant characteristics are summarised in Table 1 and reflect an overall moderate to severe level of mobility impairment. Using the walking speed thresholds to described functional walking ability [22], 20 participants were not functional walkers in everyday life (speed <0.4 ms), 18 were mobile indoors (walking speed 0.4–0.6 m/s) and six were limited outdoor walkers (speed = 0.6–0.8 m/s). Twenty-two participants scored less than 45 on the BBS, which is a proposed threshold of increased falls risk post-stroke[30]. All participants had residual paresis as none scored fully on the FM lower limb assessment.

INSERT TABLE 1

Post-hoc power analysis (GPower 3.1.3. statistical software) was carried out to ensure that our study was sufficiently powered to avoid Type 1 errors. Table 2 shows the results of this power analysis with power > 0.8 for all significant effects.

Multiple Linear Step-wise regression for each of SSWS, BB, FM and single support asymmetry revealed a model for each that included only one variable (see Table 2). The number of targets missed on the paretic side, was significantly related to FM ($F_{(1,40)}$=6.54, p=0.014). Speed of target stepping was significantly related to BBS ($F_{(1,40)}$=26.36, p<0.0001), SSWS ($F_{(1,40)}$=37.00, p<0.0001) and single support asymmetry ratio ($F_{(1,38)}$=5.57, p=.006). None of the variables of target stepping performance were significant predictors of step length asymmetry.

Figure 2 shows scatterplots and regression lines describing the relationships between functional test data and speed of target stepping (BB, SSWS & single support asymmetry, Figures 2A-C) or missed targets of paretic leg (FM – figure 2D) for each participant.

INSERT Table 2: Post-hoc Power and Multiple Linear Regression results.
INSERT FIGURE 2: LINEAR REGRESSION SCATTERPLOTS

Discussion:

This is the first study to attempt to identify relationships between the ability to alter step lengths and widths (gait adaptability) and established clinical measures of balance, motor recovery and functional walking ability in stroke survivors. The results of this study show that speed of target stepping was significantly related to balance ability (as measured by BBS), asymmetry of single support time and self-selected walking speed. The number of targets missed on the paretic side was significantly related to lower limb motor function/recovery (as measured by the Fugl-Meyer lower limb assessment). However, targets missed (either in total or on the paretic or non-paretic sides), was not predictive of asymmetry, self-selected walking speed or balance. These results suggest that fast target stepping requires good balance and temporal symmetry of gait and that accurate control of footfall location demands good paretic lower limb function. The fact that the ability to shorten, lengthen and narrow steps as required in response to environmental demands is related to functional outcomes provides support for the notion that adaptability of gait may be a key component in recovery of functional mobility and is therefore an important target for rehabilitation and clinical measurement.

Altering step lengths and widths while walking reflects the ability to maintain dynamic balance by regulating changes in the relationship between the base of support and centre of mass. So it is perhaps not surprising that performance on this target stepping task is related to a measure of balance ability. In previous studies [10] target stepping people with stroke were found to have greatest difficulty stepping to medial targets without body support; a condition with considerable demands on balance. We found no relationship between targets missed and BBS but the fact that speed of target stepping was related to BBS confirms that recovery of balance is necessary to support adaptable walking ability.

A number of studies have highlighted that time to alter foot-placement may be a key component underlying gait adaptability in stroke survivors and has been related to falls risk in older adults. For example delayed onset of foot adjustments during target stepping [10] and exacerbation of deficits in adjusting foot-placement when clearing obstacles under time pressure [5], [5, 6]have both been reported in stroke survivors. In older adults delays in the timing and accuracy of step adjustments has been related to falls risk [16, 19]. While some underlying abilities (e.g. strength) may subserve both fast SSWS and walking quickly to varied footfall locations, these are indeed separate tasks, with different sensorimotor and biomechanical demands (especially when targets elicit step adjustments) and therefore not necessarily related. Recent studies of target stepping paradigms show that attuning steps to visual targets significantly reduced SSWS, even when the patterning of these targets matched the participant's own gait pattern. Therefore the speed at which you step to targets reflects a different aspect of walking control than just SSWS over uncluttered and flat terrain. Our result showing that speed of target stepping was most highly predictive of overall gait function (as reflected by SSWS) confirms the results of these previous studies indicating that speed of altering footfall locations while walking may be an important component in the recovery of functional walking ability in stroke survivors.

Adapting footfall locations in response to environmental demands may be particularly challenging for stroke patients due to the fact that the task imposes step asymmetries on an already asymmetric walking pattern. We, therefore, thought it important to record the number of targets missed on both the paretic and non-paretic sides and to examine the relationship between symmetry of gait and gait adaptability. The mean number of targets missed on the paretic and non-paretic sides were similar in our study. Although other studies have shown differences in step adjustments between paretic and non-paretic limbs in response to variable metronome cues [11], our finding is in agreement with studies of visual target stepping paradigms [10] showing equivalent foot-placement control between the ipsilesional and contralesional legs.

Despite equivalent success of stepping to targets using paretic and non-paretic limbs we found the number of targets missed on the paretic side was individually predictive of lower limb motor function. The predictive value of the success of stepping to targets with the paretic leg on motor function corroborates evidence from previous studies [5, 15] that impairments in the control of paretic limb foot placement may be mechanistic in supporting adaptations of gait such as obstacle avoidance. A further study of obstacle avoidance identified delayed and decreased muscle activation patterns as one possible mechanism underlying diminished ability to adapt the length of the avoiding stride [6]. Our results which show a significant correlation between the number of targets missed on the paretic side and lower limb motor function further support the idea [6] that motor impairment may underlie diminished adaptability of walking.

We found that speed of target stepping was significantly predictive of single support asymmetry ratio. This finding is also consistent with previous studies which highlight the importance of single support time in functional mobility and adaptations of gait in stroke survivors i.e. single support time has been related to turning ability [7] balance control [31] and is an important determinant of gait function post-stroke [32].

A recent review of gait adaptability has called for the development of specific, comprehensive and rigorous assessments for walking adaptability [14]. Standard assessments of walking on flat, uncluttered surfaces may not be reflective of walking ability in environments where control of foot placement typically requires visually guided adaptations to avoid obstacles or place the foot in a safe location. Hence, assessment of gait adaptability and footfall control may be required in order to establish falls risk and inform the design of targeted interventions to improve walking ability post-stroke. Future studies should seek to develop target stepping paradigms as means of assessing gait adaptability and establish psychometric properties such as test-retest and inter-rater reliability as well as responsiveness to change and treatment in larger sample sizes with subgroupings for falls history.

We have sought to test adaptability of gait using a testing paradigm that is pragmatic to implement in clinical settings. However, one limitation of this target stepping paradigm is that it does not allow testing of time critical adaptations to gait. Given that many studies [5, 6, 10] have shown exacerbation of gait impairments under time restrictions it may be that assessing responses to sudden changes in environmental demands would provide even better predictions of functional outcomes. A further limitation of this study is the lack of control group. We have not included a cohort of healthy age-match controls to contrast stroke survivors' performance against. However, a previous study [20] has shown that target stepping, as a measure of gait adaptability, is a reliable measure of irregular walking with ability to discriminate between young and older subjects. The aim of this study was to provide an initial indication of whether or not performance on a target stepping paradigm showed any evidence of being a valid component/predictor of the recovery of functional mobility outcomes for stroke survivors. It remains for future research to establish discriminative sensitivity of target stepping as a paradigm for the measurement of gait adaptability. Finally we did not take any measures of attention. Given that some studies have shown that walking to external cues (particularly visual, as opposed to auditory, cues) requires greater attention than unconstrained walking [17, 18], future studies should examine the influence of altered attention and cognitive/executive function following stroke on performance of target stepping tasks.

Conclusions:

Speed of target stepping is a significant predictor of balance, comfortable walking speed and single support symmetry. Success of hitting targets with the paretic limb is a significant predictor of lower limb motor function in stroke survivors. These results suggest that fast target stepping requires good balance and temporal symmetry of gait and that accurate control of footfall location demands good paretic lower limb function. The relationships between these parameters indicate gait adaptability is a clinically meaningful target for measurement and treatment of functionally adaptive walking ability in this patient group. Target stepping paradigms may be a useful and clinically pragmatic method of both measuring and treating adaptability of gait. Future studies should examine the influence of altered attention, cognitive/executive and visuomotor function following stroke on performance of target stepping tasks and look to establish the psychometric properties of target stepping paradigms to develop standardised measures of gait adaptability.

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Figure Legends:

Figure 1 shows photographs of the target stepping layout and a schematic of an example of when a target is classed as missed (second paretic step with an X showing the target is recorded as missed).

Figure 2 shows scatterplots and regression lines describing the relationships between functional test data and speed of target stepping (BB, SSWS & single support asymmetry, Figures 2A-C) or missed targets of paretic leg (FM – figure 2D) for each participant.

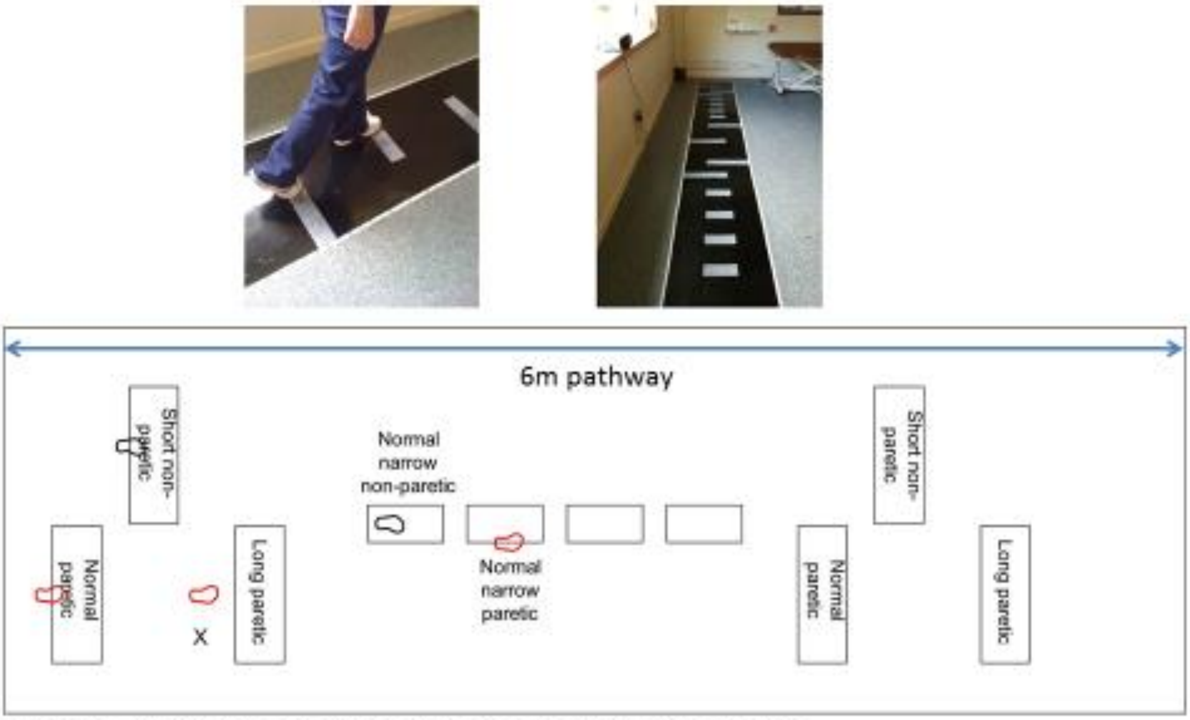

Figure 1: Methods Schematic and photographs

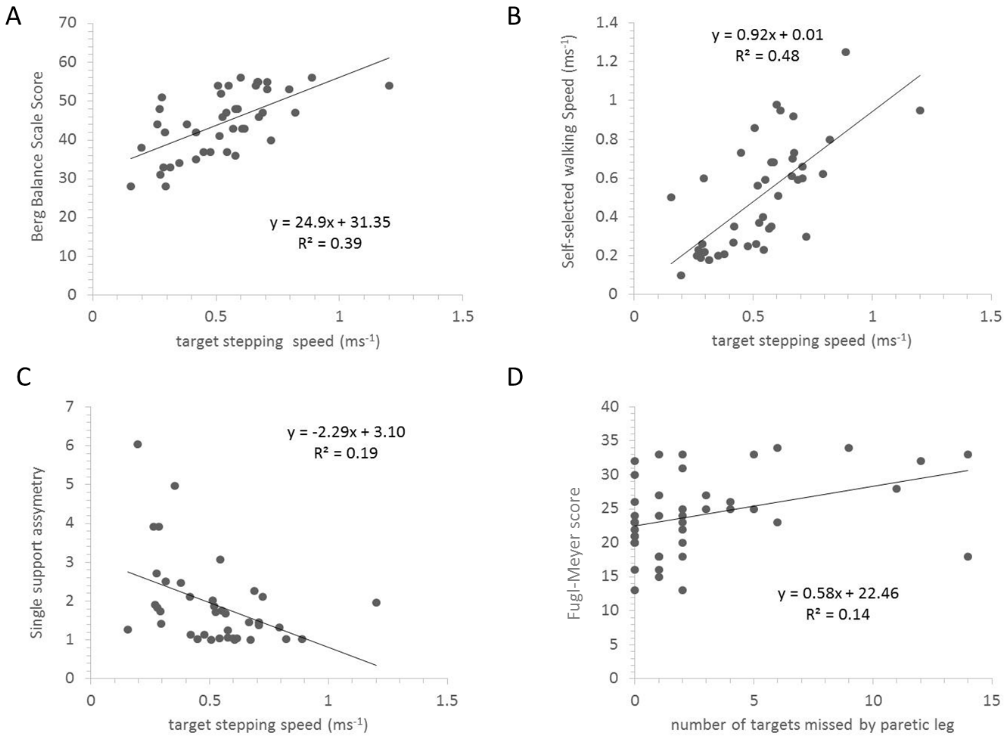

Figure 2: Scatterplots and regression lines describing the relationships between functional test data and speed of target stepping/paretic targets missed

Table 1
Participant characteristics and performance on target stepping task and clinical assessment scales. Mean speed of target stepping and mean numbers of targets missed were calculated as the average of the 6 passes of the walkway.

Descriptive statistics				
$N = 42$	Minimum	Maximum	Mean	Std. deviation
Age (years)			57.5	15.7
Gender			41.6% female	
Side of lesion			55% right, 8.3% bilateral	
Time since stroke (days)			232	363
Speed of target stepping (m/s)	0.1	1.2	0.5	0.2
Paretic targets missed	0	14	2.8	3.8
Non-paretic targets missed	0	20	2.3	4.2
Gait speed (m/s)	0.1	1.3	0.5	0.3
Berg balance score	28	56	44.4	8.2
Fugl–Meyer lower limb assessment	13	34	24.1	5.9
Single support asymmetry ratio	0.17	2.47	0.76	0.47
Step length asymmetry ratio	0.46	9.92	1.66	1.72

Table 2
Parameters for post-hoc power analysis and results of multiple linear regression are reported for each of the independent variables: Berg Balance Scale (BBS), self-selected walking speed (SSWS) and Fugl–Meyer lower limb assessment (FM).

	Power analyses					Multiple linear regression results			
	Effect size (f^2)	Noncentrality parameter (δ)	Critical (t)	Power	R^2	Variables	B	SE B	β
SSWS	0.92	6.22	1.68	**0.99**	**0.48**	(Constant)	0.01	0.086	
						Speed of target stepping	0.92	0.153	0.69
BBS	0.65	5.25	1.68	**0.99**	**0.39**	(Constant)	31.35	2.74	
						Speed of target stepping	24.90	4.84	0.63
FM	0.16	2.62	1.68	**0.82**	**0.14**	(Constant)	22.46	1.08	
						Paretic missed targets	0.58	0.22	0.37