Title: Determinants of limb preference for initiating compensatory stepping post-stroke

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ABSTRACT
Objective: To investigate the determinants of limb preference for initiating compensatory stepping post-stroke.
Design: Retrospective chart review.
Setting: In-patient rehabilitation.
Participants: Convenience sample of 49 individuals admitted to in-patient rehabilitation with post-stroke hemiparesis.
Interventions: Not applicable.
Main outcome measures: Compensatory stepping responses were evoked using a lean-and-release postural perturbation. The limb used to initiate compensatory stepping was determined. The relationships between stepping with the paretic limb and pre-morbid limb dominance, weight-bearing on the paretic limb in quiet standing, ability to bear weight on the paretic limb, pre-perturbation weight bearing on the paretic limb, and lower-limb motor recovery scores were determined.
Results: The majority (59.1%) of responses were steps initiated with the non-paretic limb. Increased lower-limb motor recovery scores and pre-perturbation weight-bearing on the non-paretic limb were significantly related to increased frequency of stepping with the paretic limb. When the preferred limb was physically blocked, an inappropriate response was initiated in 21% of trials (i.e. non-step responses or an attempt to step with the blocked limb).
Conclusions: This study reveals the challenges that individuals with post-stroke hemiparesis face when executing compensatory stepping responses to prevent a fall following a postural perturbation. The inability or challenges to executing a compensatory step with the paretic limb may increase the risk for falls post-stroke.

ABBREVIATIONS
CMSA: Chedoke-McMaster Stroke Assessment

Rapid corrective reactions are essential to regain stability and prevent a fall following a postural perturbation.[1] Compensatory steps, which increase the size of the base of support, are a particularly important type of balance-recovery reaction.[1] Such 'change-in-support' reactions are the preferred response to a loss of balance,[2, 3] and the 'final' defense to prevent a fall.[3] Compensatory stepping reactions are characterized by: 1) extremely rapid onset and movement speed,[4] 2) amplitude and trajectory scaled to the degree of instability,[3] and 3) ability to accommodate environmental circumstances.[5] These characteristics place tremendous demands on those with stroke, potentially increasing the risk for falls.

A unilateral focal stroke typically results in contralesional sensori-motor impairment that leads to asymmetry in performance of functional activities.[6] This functional asymmetry presents a challenge for the control of compensatory stepping: an individual with hemiparesis post-stroke must rely on the paretic lower-limb for either initiating the response or accepting weight to initiate a step with the non-paretic limb. Previously, we observed that when young healthy individuals stand asymmetrically they will initiate compensatory stepping with the less-loaded limb.[7] However, in a pilot study we observed that individuals with stroke tended to initiate compensatory stepping with the non-paretic limb despite bearing more weight on that limb.[8] Unloading the non-paretic limb prior to rapid stepping takes extra time which may compromise stability. When stroke patients' non-paretic limb was physically blocked with an obstacle they continued to attempt to initiate stepping with that limb,[8, 9] further demonstrating reluctance to step with the paretic limb. The desire to step with the non-paretic limb, regardless of environmental constraints, may reflect challenges in the ability to rapidly execute and accurately place a step with the paretic limb due to limb-specific sensori-motor impairments.

The objectives of this study were to: 1) ascertain the preferred limb for initiating compensatory stepping; 2) investigate the determinants of limb preference for initiating compensatory stepping; and 3) investigate the consequences of initiating compensatory stepping with the paretic limb, among individuals with stroke. From our previous pilot work[8, 9] we hypothesized that, for individuals with post-stroke hemiparesis, the non-paretic limb is preferred for initiating compensatory stepping. With regard to our second objective, we anticipated that limb preference for stepping would be related to paretic-limb motor impairment. The Chedoke-McMaster Stroke Assessment (CMSA) is frequently used clinically to assess motor impairment; therefore we hypothesized that reduced frequency of stepping with the paretic limb would be related to lower CMSA scores. Conversely, a reduced ability to bear weight on the paretic limb might discourage initiating stepping with the non-paretic limb; therefore, we hypothesized that increased frequency of initiating stepping with the paretic limb would be related to reduced ability to bear weight on the paretic limb. Regarding our third objective, we hypothesized that increased frequency of initiating compensatory stepping with the paretic limb would be related to an increased rate of failed responses (i.e. reliance on the safety harness or physical therapist assistance to prevent a fall), particularly for those with severe lower-limb motor impairment. We also sought to determine whether physically blocking the preferred limb would promote stepping with the non-preferred limb.

METHODS

Participants

We conducted a retrospective chart review of patients with stroke who were assessed in the Balance Mobility and Falls Clinic at the Toronto Rehabilitation Institute. This clinic provides assessment of quiet standing balance and perturbation-evoked compensatory stepping as part of routine care to individuals with stroke attending in-patient rehabilitation. Assessment of compensatory stepping occurred soon after admission to rehabilitation or, for patients who could not stand independently on admission, as soon as they regained independent stance. We included those patients admitted within a

1-year period who completed assessment of perturbation-evoked compensatory stepping (described below). In order to focus the analysis on individuals with stroke-related unilateral deficits, we excluded those with sensori-motor impairment of both lower limbs or those with lower-limb joint replacement. Within the time period, 97 patients completed assessment of perturbation-evoked stepping reactions; 18 were excluded due to bilateral sensori-motor impairment, 6 were excluded due to lower-limb joint replacement, and 24 were excluded because they did not complete enough trials. Forty-nine individuals met the criteria for inclusion in the review. All assessments were performed by a trained physical therapist. Patients' age, sex, stroke location, side of paresis, pre-morbid limb dominance, and CMSA[10] leg and foot, and National Institutes of Health Stroke Scale[11] scores were extracted from clinical charts. Pre-morbid limb dominance was assessed by asking patients which hand they wrote with and which foot they would have used to kick a ball prior to their stroke. The CMSA assigns a score between 1-7 according to the level of motor recovery in the foot and leg and is frequently used to evaluate motor recovery post-stroke in clinical settings. Higher CMSA scores indicate improved motor recovery. The CMSA foot and leg scores have good intra-rater (ICCs=0.94-0.98) and inter-rater (ICCs=0.85-0.96) reliability.[10]

The retrospective review was approved by the institution's Research Ethics Board; a waiver of patient consent for inclusion in the review was approved.

Assessment of weight-bearing on the paretic limb

Weight-bearing on the paretic limb was measured while patients stood with 1 foot on each of 2 force plates[a] in a standardized position (heel centers 17cm apart, 14° between the long axes of the feet[12]) under 2 conditions: standing quietly with eyes open for 30s and bearing as much weight as possible on the paretic limb for up to 20s. A shorter duration was used for the maximal weight-bearing condition as it is less well-tolerated than the quiet stance condition. The amount of weight borne on the paretic limb, expressed as a percentage of body weight and averaged over the duration of the trial, was calculated. The quiet stance condition provided an estimate of the patients' natural tendency to bear weight on the paretic limb, whereas the maximal weight-bearing condition revealed the patients' capacity to bear weight on the paretic limb.

Assessment of compensatory stepping reactions

A 'lean-and-release' postural perturbation system was used to evaluate control of compensatory stepping.[7] Patients stood in the standardized foot position[12] with 1 foot on each of the 2 force plates and leaned forward with approximately 10% of body weight supported by a cable attached to the wall. The standardized foot position ensured that the width of the base of support was similar across subjects and the foot orientation was symmetrical for each subject. In a previous study including healthy young adults, a lean of 11% body weight corresponded to a whole-body lean (i.e. ankle angle) of approximately 9° from vertical.[7] At an unexpected time, the cable was released and patients started to fall forward. Perturbations of this type and magnitude consistently evoke compensatory stepping reactions in young healthy individuals.[7] Patients completed 2 conditions: 'preferred response' and 'encouraged use'. In the preferred response trials there were no instructions or constraints placed on reactions. In the encouraged-use trials, the patients' preferred limb for initiating compensatory stepping (i.e. the limb used most frequently in the preferred response trials) was physically blocked with the physical therapist's hand or foot approximately 5cm in front of the shin. This distance was chosen to be sufficiently close so that patients could not execute an effective step without colliding with the therapist's limb, but not so close that a collision would occur with small post-perturbation limb movements. We included only those individuals who completed at least 5 trials in the preferred response condition. Patients wore a safety harness affixed to an overhead frame to prevent a fall in the

event of a failure to recover balance. A physical therapist also stood near patients to assist them if they were unable to regain stability alone.

A load cell[b] placed in series with the cable attached to the patient's back measured forces placed on the cable prior to the perturbation. The load cell output was monitored prior to the perturbation to ensure consistency of pre-perturbation lean. The load cell was also used to detect perturbation onset time (i.e. time when force recorded was <1N). Vertical ground reaction forces recorded by the force plates were used to determine pre-perturbation load on the paretic limb; this was defined as the percentage of body weight on the paretic limb averaged over 1s before the perturbation. Load cell and force plate data were sampled at 256Hz. The assessment was video-recorded. The limb used to initiate compensatory stepping was determined from the videos and force plates; a step occurred if the vertical force on one force plate was <1% body weight and/or there was noticeable forward movement of the foot on the video. Videos were also reviewed to determine if assistance was required from the safety harness or physical therapist to prevent a fall.

Statistical analysis

The frequency of step initiation with the paretic and non-paretic limb was determined for all trials completed by all patients and for each individual patient. A patient was deemed to have a strong preference for stepping with a specific limb if s/he stepped with that limb in all preferred response trials. Three groups of patients were identified: those with a strong preference for initiating stepping with the paretic limb, those with a strong preference for initiating stepping with the non-paretic limb, and those with no clear limb preference (i.e. initiated stepping with both limbs).

Multiple logistic regression with generalized estimating equations and repeated measures[13] (to account for multiple observations per participant) was used to establish the determinants of limb selection among individual trials. An autoregressive correlation structure was assumed as behavioral characteristics could change with repeated exposure to the perturbation (i.e. short term 'learning effect'). The dependent logistic variable was the limb used (paretic versus non-paretic limb). Trial- and patient-specific variables were included as predictors. The trial-specific factor was pre-perturbation load on the paretic limb. Patient-specific factors were quiet stance load on the paretic limb, maximal paretic limb load, limb impairment (CMSA-foot and -leg scores) and pre-morbid limb dominance. A second multiple logistic regression approach was used to determine if increased frequency of stepping with the paretic limb, covaried with CMSA-foot and/or -leg scores, was related to an increased frequency of failed responses. Correlation analyses were completed to determine if independent variables were correlated with each other. Regression analyses were repeated with highly-correlated variables ($\rho>0.6$) removed to determine their impact on the statistical inference. For all statistical analyses, alpha was 0.05.

RESULTS

Limb preference for initiating compensatory stepping

Two individuals avoided stepping in all preferred response trials and were excluded from further analysis. There were 235 preferred response trials completed by the remaining 47 patients. Of these, 59.1% (139/235) were stepping responses initiated with the non-paretic limb, 37.0% (87/235) were initiated with the paretic limb, and in 3.8% (9/235) of trials there was no stepping response. More than half of the patients showed a strong limb preference for initiating stepping; 40.4% (19/47) of patients initiated stepping with the non-paretic limb in all trials and 14.9% (7/47) initiated stepping with the paretic limb in all trials, whereas 44.7% (21/47) initiated stepping with both the paretic and non-paretic limb. Table 1 provides characteristics of the overall and patient sub-groups.

Table 1: Participant characteristics. Values presented are means with the standard deviation and range in parentheses for numerical data, or counts with the percentage of the group in parentheses for frequency data

	Total sample (n=47)	No preference (n=21)	Non-paretic preference (n=19)	Paretic preference (n=7)
Age (years)	59.8 (14.7; 26 – 88)	57.9 (15.0; 26 – 84)	61.9 (12.3; 36 – 79)	60.0 (21.1; 37 – 88)
Sex				
Women	15 (31.9)	10 (47.6)	2 (10.5)	3 (42.9)
Men	32 (68.1)	11 (52.4)	17 (89.5)	4 (57.1)
Pre-morbid limb dominance				
Right	44 (93.6)	19 (90.5))	18 (94.7)	7 (100)
Left	3 (6.4)	2 (4.3	1 (5.3)	0 (0)
Admission time post-stroke (days)	16.3 (14.2; 5 – 89)	13.3 (5.5; 6 – 28)	20.6 (20.1; 5 – 89)	13.4 (11.0; 7 – 38)
Assessment time post-stroke (days)	27.5 (18.9; 8 – 91)	22.4 (10.3; 8 – 44)	34.9 (24.6; 12 – 91)	23.0 (17.1; 9 – 57)
Affected hemisphere				
Right	12 (25.5)	5 (23.8)	4 (21.1)	3 (57.1)
Left	27 (57.5)	12 (57.1)	11 (57.9)	4 (42.9)
Both*	8 (17)	4 (19.1)	4 (21.1)	0 (0)
Paretic side				
Right	29 (61.7)	13 (61.9)	13 (68.4)	3 (42.9)
Left	18 (38.3)	8 (38.1)	6 (31.6)	4 (47.1)
Stroke type				
Ischemic	38 (80.9)	20 (95.2)	12 (63.2)	6 (85.7)
Haemorrhagic	7 (14.9)	1 (4.8)	6 (31.6)	0 (0)
Transforming to haemorrhagic	2 (4.3)	0 (0)	1 (5.3)	1 (14.3)
National Institutes of Health Stroke Scale	3.1 (2.8; 0 – 12)	2.8 (2.2; 0 – 8)	3.9 (3.5; 0 – 12)	2.0 (1.7; 0 – 4)
CMSA-leg	4.7 (1.2; 2 – 7)	5.1 (1.1; 3 – 7)	4.3 (1.2; 2 – 7)	4.9 (1.2; 3 – 6)
CMSA-foot	4.5 (1.2; 2 – 7)	4.9 (1.2; 3 – 7)	4.0 (1.2; 2 – 6)	5.0 (1.4; 2 – 6)
Quiet stance load on paretic limb (% body weight)	46.4 (8.3; 20 – 70)	45.0 (7.2; 20 – 52)	47.3 (10.1; 31 – 70)	48.3 (5.6; 38 – 53)
Maximal load on paretic limb (% body weight)	78.1 (9.5; 54 – 94)	80.1 (9.9; 60 – 94)	76.3 (9.2; 54 – 93)	76.9 (8.6; 67 – 88)

*Patients with stroke affecting both hemispheres typically had a previous and/or small stroke in the hemisphere contralateral to the current stroke. In these cases there was noticeable sensori-motor impairment on only one side of the body.

Determinants and consequences of limb preference

Pre-perturbation load on the paretic limb and CMSA-foot scores were significantly related to limb preference (p-values<0.02). Specifically, increased CMSA-foot scores and reduced pre-perturbation paretic-limb load were related to increased frequency of initiating stepping with the paretic limb. Odds ratios and 95% confidence intervals are included in Table 2. For illustration, using the odds ratios in model 3 in Table 2, an individual with a CMSA-foot score of 2 would need to bear only 27% body weight on the paretic limb prior to the perturbation in order to have a 50% probability of initiating stepping with the paretic limb. Conversely, an individual with a CMSA-foot score of 7 who bears 62% of body weight on the paretic limb has a 50% probability of initiating stepping with the paretic limb.

Table 2: Modelling the likelihood of initiating stepping with the paretic limb. Values presented are odds ratios with 95% confidence intervals in brackets. The odds ratios indicate the odds of stepping with the paretic limb for each unit increase in the independent variable, adjusted for other variables in the model. Model 1 included all factors whereas models 2 and 3 only included those factors that showed statistically significant relationships in models 1 and 2, respectively (alpha=0.05).

	Model 1	**Model 2**	**Model 3**
Dominant limb affected (no=0; yes=1)	2.25 [0.66 – 7.80]	-	-
Quiet stance load on paretic limb (% body weight)	1.09 [1.01 – 1.18]*	1.06 [0.97 – 1.16]	-
Maximal load on paretic limb (% body weight)	1.03 [0.97 – 1.09]	-	-
Pre-perturbation load on paretic limb (% body weight)	0.83 [0.77 – 0.89]***	0.85 [0.80 – 0.91]***	0.86 [0.81 – 0.92]***
CMSA-foot (score)	3.56 [1.54 – 8.20]**	2.61 [1.46 – 4.64]**	2.95 [1.64 – 5.25]***
CMSA-leg (score)	0.56 [0.25 – 1.25]	-	-

*p<0.05; **p<0.01; ***p<0.001

CMSA-foot and -leg scores were highly correlated with each other (correlation coefficient=0.72; $p<0.0001$). Therefore, the initial multiple logistic regression (model 1 in Table 2) was repeated twice, once with CMSA-foot scores removed and once with CMSA-leg scores removed. Removal of either CMSA-foot or -leg scores from the initial model did not affect the results (i.e. CMSA-leg scores were not significantly related to frequency of initiating stepping with the paretic limb when CMSA-foot scores were removed from the model).

Load on the paretic limb appeared to differ between the quiet stance trial and prior to the perturbation. Therefore, we conducted additional 2-tailed paired t-tests to compare differences in asymmetry between conditions (Table 3). On average, patients tended to load the paretic limb more prior to the perturbation than in quiet stance ($t_{46}=3.20$, $p=0.003$). This difference was significant among those with a strong preference for stepping with the non-paretic limb ($t_{18}=4.20$, $p<0.001$) and with no strong limb preference ($t_{20}=2.77$, $p=0.012$), but not among those with a strong preference for stepping with the paretic limb ($t_{6}=-1.66$, $p=0.15$).

Table 3: Comparison between quiet stance and pre-perturbation load on the paretic limb. Values presented are means with standard deviation in parentheses. The p-value is for the paired t-test comparing stance load on the paretic limb between the two conditions (alpha=0.05).

	Quiet stance (% body weight)	**Pre-perturbation (% body weight)**	*p-value*
Total sample (n=47)	46.4 (8.3)	50.4 (10.6)	*0.003*
No preference (n=21)	45.0 (7.2)	48.6 (9.2)	*0.012*
Non-paretic preference (n=19)	47.3 (10.1)	55.3 (10.6)	*<0.001*
Paretic preference (n=7)	48.3 (5.6)	42.7 (9.6)	*0.15*

In 21.7% (49/226) of trials with a stepping response, physical-therapist or support-harness assistance was required to prevent a fall to the floor. Increased frequency of initiating stepping with the paretic limb was not related to increased frequency of external assistance to prevent a fall (odds ratio: 1.80 [0.87 – 3.73]; $p=0.11$). However, reduced motor recovery in the paretic limb (i.e. reduced CMSA-foot score) was related to increased frequency of external assistance (odds ratio: 0.47 [0.28 – 0.79]; $p<0.0042$). Using these odds ratios, an individual with a CMSA-foot score of 2 who steps with the paretic limb has a 73% probability of requiring assistance, and a 60% probability of requiring assistance if s/he steps with the non-paretic limb. Conversely, an individual with a CMSA-foot score

of 7 has a 6% probability of requiring assistance following a step with the paretic limb and a 3% probability of requiring assistance following a step with the non-paretic limb.

Limb use in encouraged-use trials

Analysis of encouraged-use trials was limited to those patients with a strong preference for initiating stepping with one limb. Twenty-three individuals with a strong limb preference (17 non-paretic, 6 paretic) completed the encouraged-use condition in which the preferred limb was blocked with the physical therapist's hand or foot; limited tolerance prevented two participants from completing this condition. A total of 105 encouraged-use trials were completed, and in 79% (83/105) of these trials individuals stepped with the appropriate (unblocked) limb. Of the 22 trials with an inappropriate response, 15 involved attempts to step with the blocked limb and 7 involved no stepping response. Assistance was required to prevent a fall in 50% (11/22) of trials with an inappropriate response compared with only 9.6% (8/83) of trials with an appropriate response.

DISCUSSION

This study demonstrates that, among individuals with post-stroke hemiparesis, compensatory steps are more frequently initiated with the non-paretic than the paretic limb, supporting observations from previous pilot work.[8] In our previous study, we speculated that a preference for initiating stepping with the paretic limb was not related to lower-limb motor impairment. However, in the current study we found that increased CMSA-foot scores (less motor impairment), combined with reduced pre-perturbation load on the paretic limb, were related to increased frequency of stepping with the paretic limb. Because of the importance of hip and knee flexion to the control of step execution and hip abduction to stability control upon step termination one might expect motor impairment in the leg to be more strongly related to limb choice than motor impairment in the foot. However, foot and ankle control is integral to both the generation of sufficient toe clearance during the swing phase and weight acceptance at step termination. Despite the reluctance to step with the paretic limb among those with lower-limb motor impairment we did not find any evidence of increased response failures when stepping with the paretic limb.

Most patients were able to initiate compensatory stepping with the non-preferred limb when the preferred limb was blocked, but this was not observed previously.[8] In the previous study we used objects to block the preferred limb, but in the current study the preferred limb was blocked with the physical therapists' limb. In the previous study, those reluctant to step with the unblocked limb tended to simply step into the obstacles or kick them out of the way. We interpret the current finding as patients having a greater perceived negative consequence of attempting to initiate compensatory stepping with the blocked limb (i.e. colliding with the therapist instead of an inanimate object).[9] It is important to note, however, that despite the relative predictability of both perturbation direction and limb constraint, in over 20% of encouraged-use trials patients initiated an inappropriate response; that is, they did not step at all or they attempted to step with the blocked limb. Inappropriate responses typically resulted in external assistance to prevent a fall. In order to be able to prevent a fall following an unpredictable real-world postural perturbation (i.e. perturbation in any possible direction in a potentially cluttered environment) it is essential to be able to step with either limb and in any direction. Young healthy individuals can navigate environmental obstacles when executing compensatory steps.[14] The current study reveals the limited capacity of individuals with stroke to adapt to even relatively simple environmental constraints during compensatory stepping. Individuals with stroke fall more often than age-matched healthy individuals.[15] Limited adaptability of compensatory stepping responses may be one factor that increases falls risk post-stroke.

These results have potential implications for rehabilitation of dynamic balance control post-stroke. 'Encouraged-use' or constraint-induced methods are well-established for rehabilitation of upper-limb function post-stroke with a focus on the paretic limb.[16] However the control of the lower limbs during balance and mobility is importantly co-dependent (e.g. during stepping when one limb is used to step, the other to stabilize). As a result the specific use of one limb over another is influenced not only by the stroke and associated limb-specific impairments but also adaptive control strategies. When one can isolate the limbs in non-balance tasks one can focus on encouraging use of the paretic limb (e.g. recumbent stepping[17]). Encouraged-use of the lower limb for rehabilitation of balance and mobility post-stroke has been typically delimited to increasing weight-bearing on the paretic limb.[18, 19] However, we argue that, based on the results of this study, it may be equally important to employ the principles of encouraged use to facilitate the use of the non-preferred limb, which is typically the paretic limb, for executing movements such as compensatory steps.[9] It is important to note that, while most patients demonstrated a clear preference for initiating stepping with one limb, 45% of patients initiated compensatory stepping with both limbs in the preferred response trials. These individuals have the capacity to freely execute stepping with either limb when no environmental constraints are present. The encouraged-use approach described above would not necessarily be appropriate for these individuals.

Study limitations

This study involved a retrospective review of data collected for clinical purposes. Within the clinical setting it is not feasible to use motion analysis to evaluate kinematic features of balance reactions (e.g. limb trajectory, step length, centre of mass control). While the comparison of characteristics of stepping responses between the paretic and non-paretic limb was beyond the scope of this study, such analysis with the inclusion of kinematic data may provide insight into how dyscontrol of paretic-limb stepping responses influences limb choice. Similarly, our analyses considered the relationship between lower-limb motor control (i.e. CMSA scores) and limb preference for compensatory stepping. Limb preference might also be affected by stroke-related impairments in cognition, attention (e.g. hemi-spatial neglect), and sensation (e.g. lower-limb proprioception); however, these measures were not available in the current review.

Additionally, the prevalence of initiating compensatory stepping with the paretic limb in the current study was higher than expected given our previous work.[8] This may be due to the type of perturbation used; the perturbation direction in the current study was entirely predictable whereas an unpredictable (antero-posterior) perturbation was employed in the previous study. Increased predictability may have lead to pre-planning for stepping. Patients with a preference for stepping with the non-paretic limb maintained weight shift more towards the paretic limb during perturbation trials than in quiet stance. This may indicate that these participants are aware of limitations in the ability of the paretic limb to contribute to balance recovery following a postural perturbation and adopt an adaptive strategy to prepare to execute a step with the non-paretic limb by increasing load on the paretic limb.

CONCLUSIONS

In support of our earlier pilot work, we found that individuals with post-stroke hemiparesis were generally reluctant to initiate compensatory stepping with the paretic limb. Limited adaptability of compensatory stepping responses may place these individuals at an increased risk for falls. Further research is required to determine the link to falls and rehabilitation strategies to encourage use of the non-preferred limb for executing compensatory steps.

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