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Walking through the looking glass: Adapting gait patterns with mirror feedback

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Clinical locomotor research seeks to facilitate adaptation or retention of new walking patterns by providing feedback. Within a split-belt treadmill paradigm, sagittal plane feedback improves adaptation but does not affect retention. Representation of error in this manner is cognitively demanding. However, it is unknown in this paradigm how frontal plane feedback, which may utilize a unique learning process, impacts locomotor adaptation. Frontal plane movement feedback has been shown to impact retention of novel running mechanics but has yet to be evaluated in gait conditions widely applicable within neurorehabilitation, such as walking. The purpose of this study was to investigate the effects of frontal plane mirror feedback on gait adaptation and retention during split-belt treadmill walking. Forty healthy young adults were divided into two groups: one group received mirror feedback during the first split-belt exposure and the other received no mirror feedback. Individuals in the mirror feedback group were asked to look at their legs in the mirror, but no further instructions were given. Individuals with mirror feedback displayed more symmetric stance time during the first strides of adaptation and maintained this pattern into the second split-belt exposure when no feedback was provided. Individuals with mirror feedback also demonstrated more symmetric double support time upon returning to normal walking. Lastly, the mirror feedback also allowed individuals to walk with smaller gait variability during the final steps of both split-belt exposures. Overall, mirror feedback allowed individuals to reduce their stance time asymmetry and led to a more consistent adapted pattern, suggesting this type of feedback may have utility in gait training that targets symmetry and consistency in movement.

1. Introduction

The ability to adopt and learn new walking patterns is critical for safe and efficient mobility in complex and dynamic environments; still, optimal methods for promoting skill acquisition in walking are not resolved. Learning novel gait mechanics is crucial for gait rehabilitation in patient populations, such as those with hemiplegic gait after a stroke, who need to relearn normal walking. As a result, efforts in locomotor rehabilitation research have focused on understanding factors that facilitate gait adaptation and learning (Balasubramanian et al., 2014; Eng and Tang, 2007; Hollands et al., 2013; Timmermans et al., 2016). Providing feedback is one such factor with the potential to improve the gait rehabilitation process (Eng and Tang, 2007; Hollands et al., 2013; Timmermans et al., 2016).

Models of motor adaptation and learning suggest providing additional feedback of behavior could influence adaptation and retention of a movement (Malone and Bastian, 2010; Newell et al., 2003; Roemmich et al., 2016; Sharma et al., 2016; Willy et al., 2012). For instance, individuals with patellofemoral pain were able to improve their running mechanics when provided a frontal plane mirror image of their body and given verbal cues about their running (Willy et al., 2012). Examining gait adaptability, the split-belt treadmill is an ideal tool for testing the effects of feedback on gait adaptation as it elicits the adjustment of an already learned walking pattern to accommodate novel demands and has demonstrated efficacy in improving walking symmetry after stroke (Reisman et al., 2013, 2010b, 2009, 2007). Previous split-belt treadmill walking studies that manipulated corrective feedback have shown visual feedback (e.g. video projection of the sagittal view of a participant's lower limbs or visual representation of step lengths) results in faster step length adaptation (Malone and Bastian, 2010; Roemmich et al., 2016), but has no impact on retention (Roemmich et al., 2016). Visual feedback of the sagittal plane provides an indication that

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an error has occurred (e.g. step lengths are different between legs), but may influence only certain aspects of gait adaptation.

Corrective/instructive feedback is a critical component of motor learning paradigms with the nature of feedback lying within the continuum between explicit and implicit motor learning. Explicit motor learning generates verbal knowledge of movement performance, involves cognitive processes and is dependent on working memory, whereas implicit learning progresses with no or minimal increase in verbal knowledge of movement performance and without awareness (Kleynen et al., 2015). Explicit cueing (Won and Jiang, 2015) with direct representation of error likely engages cognitive processes in a way that fails to promote motor learning (Fitts and Posner, 1967), whereas motor skills learned under more implicit conditions (i.e. without declarative knowledge gained from corrective performance feedback) are more stable and resilient to perturbation, such as stress (Hardy et al., 1996; Masters, 1992) and fatigue (Masters et al., 2008; Poolton et al., 2007). Indeed, motor learning protocols that do not rely on cognitive functions may facilitate rehabilitative benefits in populations with gait and cognitive comorbidity, such as individuals post-stroke (Hochstenbach et al., 1998; Lee et al., 1994). Thus, feedback that indirectly provides information about the walking pattern without providing corrective feedback or verbal instruction may facilitate both adaptation and retention of gait patterns.

Mirror feedback in the absence of explicit verbal instruction represents a more implicit motor learning design, capable of providing real-time visual information about locomotor kinematics. Yet there is a gap in evidence regarding the effect of frontal plane mirror feedback on adaptation and retention of outcomes related to gait symmetry and variability. Therefore in this study, we sought to investigate the effects of a real-time clinically feasible form of feedback that gives less direct perception of error during split-belt treadmill walking, but still provides relevant information about gait mechanics (e.g. general coordination) during a primarily sagittal plane perturbation. To accomplish this, we used mirror-based frontal plane visual feedback to provide participants a view of their body mechanics during adaptation to the novel walking paradigm. We hypothesized mirror feedback would reduce the number of steps needed to adapt and mitigate the magnitude of initial asymmetry in response to the perturbation. Additionally, because this visual plane provides less overt representation of error while still enhancing sensory information, we hypothesized feedback would also enhance retention and reduce the variability of the adapted pattern on the split-belt treadmill.

2. Methods

2.1. Subjects

Forty healthy young adults [18 males, 22 females, age (mean ± SD) 21 ± 3 years, height 1.7 ± 0.1 m, mass 67.3 ± 11.6 kg, 5 ± 2 h/week physical activity] naïve to the split-belt treadmill volunteered to participate. At the time of recruitment, all subjects were physically active as defined by participation in a minimum of 30 min of physical activity at least two times per week. Participants were excluded if they were currently injured or suffered an injury within the last six months that limited physical activity for more than three days. Participants were also excluded if they had any medical or neurological disorders or if they had a previous surgery to their back or lower extremities.

2.2. Procedures

All procedures were explained and written consent was obtained as approved by the Institutional Review Board. Individuals were divided into a mirror feedback group [9 males, 11 females, age 21 ± 3, height 1.7 ± 0.1 m, mass 67.5 ± 8.4 kg, 5 ± 2 h/week physical activity] or a control group with no feedback [9 males, 11 females, age 21 ± 3, height 1.7 ± 0.1 m, mass 67.0 ± 14.4 kg, 5 ± 2 h/week physical activity]. Passive reflective markers were placed on the participant in accordance with the Vicon Plug-In Gait lower body model. Kinematic data were collected using an eight-camera, three-dimensional motion analysis system (Vicon Motion Systems, Centennial, CO, USA) at a sampling frequency of 120 Hz.

After a ten-minute treadmill accommodation period, participants walked for five minutes at 0.5 m/s with both belts moving together (BASELINE condition). All participants were instructed to look at an X located at eye level on the wall three meters in front of them. The belts decoupled and participants walked for 15 min at a 3:1 split (1.5 m/s, 0.5 m/s) with their non-dominant leg on the fast belt (ADAPT condition). A 3:1 split ratio was chosen to create a larger perturbation as higher speed ratios have been shown to produce greater asymmetries (Reisman et al., 2005). Individuals in the mirror feedback group had a mirror placed two meters in front of them that reflected their lower extremity from the pelvis to the feet. These individuals were instructed to look at their legs in the mirror while walking in the ADAPT condition, but no other instructions were given. Participants in the no feedback group had no mirror and were instructed to look at the X on the wall. Following the ADAPT condition, the mirror was removed for the mirror feedback group and all participants were instructed to look at the X on the wall while walking with both belts moving at 0.5 m/s for 10 min (DE-ADAPT condition). Finally, individuals returned to a 3:1 split ratio for 10 min (RE-ADAPT condition) and neither group received feedback or instructions. Participants were reminded to look at either the X on the wall or their legs in the mirror (depending on the group and condition) if researchers noticed they were not attending to the appropriate target, however no measure of attention was recorded. Participants were asked to place their hands on handrails while walking. This approach was chosen to ensure the view from the mirror was consistent in the mirror group. The no feedback group also used handrails to remove any influence of handrail use across groups.

2.3. Data analysis

Gait events were automatically detected using custom-written MATLAB software (Mathworks, Natick, MA, USA) and then visually confirmed. Heel strikes were first identified relative to when the heel marker velocity switched from positive to negative in the path of progression and toe-offs were identified relative to when the toe marker velocity switched from negative to positive in the path of progression as defined by the laboratory coordinate system. Four gait cycle parameters were used to characterize kinematics: limb excursion, stance time, step length, and double support time. Limb excursion was defined as the anterior-posterior distance traveled by the ankle marker from heel-strike to toe-off (Hoogkamer et al., 2014; Reisman et al., 2010a). Stance time was defined as the percentage of the gait cycle between heel-strike and subsequent toe-off of the same limb. Step length was defined as the anterior-posterior distance between the ankle markers at heel-strike. Double support time was defined as the percentage of the gait cycle between heel-strike and subsequent toe-off of the opposite limb. Asymmetry was defined for each gait parameter as (fast leg parameter − slow leg parameter)/(fast leg parameter + slow leg parameter) (Roemmich et al., 2014).

Number of steps to adapt were quantified for step length and double support time asymmetry as previously described by Malone and Bastian (2010) with the modification that the plateau range was defined using the mean ± standard deviation of the last 30 steps of BASELINE, not ADAPT (Fig. 1). Asymmetry curves were smoothed using a moving average and binned by three steps. The number of steps to adapt was defined as the number of steps needed to achieve five consecutive steps within the plateau range. The standard deviation of the last 30 steps of BASELINE, ADAPT and RE-ADAPT were calculated for all four gait parameter asymmetries to quantify the final adapted condition (Fig. 1). Change scores were calculated by removing BASELINE standard deviations from the ADAPT and RE-ADAPT conditions to remove any inherent group differences in variability. Positive values indicated an increase in variability from BASELINE and negative values indicated a decrease in variability from BASELINE. To compare magnitude of asymmetry, all gait parameter asymmetries were averaged over the last five strides of BASELINE, the first five strides of ADAPT (EARLY), the first five strides at the seven-and-a-half-minute mark of ADAPT (MID), the last five strides of ADAPT (LATE), and the first five strides of DE-ADAPT and RE-ADAPT. BASELINE asymmetry was removed from all subsequent conditions to obtain a true magnitude of change induced by the decoupling of belts during adaptation for each participant.

2.4. Statistical analysis

To obtain normal or near-normal distributions, outliers were identified using the median absolute deviation (MAD) for all dependent variables with a threshold of 2.5 (Eq. (1)) (Leys et al., 2013; Miller, 1991). All values that fell above or below the threshold were replaced with the upper or lower bound accordingly. After accounting for outliers, all dependent variables met the assumptions necessary for their proposed statistical tests aside from two of the four dependent variables for number of steps to adapt. Blom transformations were applied separately to each of the four outcome measures (number of steps to adapt step length and double support time during ADAPT and RE-ADAPT) to achieve normality (Blom, 1958).

$$M - 2.5 * MAD < x_i < M + 2.5 * MAD \quad (1)$$

A series of t-tests were performed to assess differences in the number of steps to adapt step length and double support time asymmetry during ADAPT and RE-ADAPT ($P < 0.0125$). A 2×2 (Group × Condition) repeated measures MANOVA was performed to analyze differences in standard deviation change scores of the final adapted pattern for limb excursion, stance time, step length, and double support time asymmetries during ADAPT and RE-ADAPT (standard deviation: $P < 0.05$). A 2×5 (Group × Condition) repeated measures MANOVA was performed to analyze differences in the magnitude of asymmetry for all gait parameters during EARLY, MID, LATE, DE-ADAPT, and RE-ADAPT ($P < 0.0175$). Greenhouse-Geisser corrected statistics were reported when sphericity assumptions were violated. To account for multiple comparisons, Benjamini Hochberg corrected significance levels were applied to all statistical analyses. SPSS was used for all statistical analyses (v24, SPSS Inc., Chicago, IL, USA) and G*Power was used for effect size calculations (v3.1) (Faul et al., 2007). Cohen's *d* was calculated to determine effect size for t-tests and post hoc decompositions with ranges of 0.20–0.50 as small, 0.50–0.80 as medium, and greater than 0.80 as large; Cohen's *f* was calculated to determine effect size of main effects for two-way MANOVAs with ranges of 0.10–0.25 as small, 0.25–0.40 as medium, and greater than 0.40 as large (Cohen, 1977).

3. Results

Demographic data (age, mass, height, and physical activity level) were not statistically different between groups ($P > 0.60$).

3.1. Number of steps to adapt

One individual in the mirror group and four individuals in the no-feedback group did not return to baseline step length symmetry (based on our mathematical criteria) and thus were removed from the step length portion of the analysis. All participants were able to return to baseline double support time symmetry. The statistical analyses failed to identify significant differences between groups in number of steps to adapt step length during ADAPT [t(31.18) = 0.34, $P = 0.74$, $d = 0.11$] or RE-ADAPT [t(33) = 0.59, $P = 0.56$, $d = 0.20$] (Table 1). Individuals in the mirror feedback group required more steps to adapt their double support time during ADAPT [t(38) = −2.69, $P = 0.01$, $d = 0.85$] but no group differences were present during RE-ADAPT [t(35) = −0.42, $P = 0.68$, $d = 0.14$] (Table 1). Outlier trimmed values (pre-Blom transformation) are presented in Table 2 for clinical reference.

3.2. Final adapted pattern

A significant main effect of feedback group was revealed at the multivariate level for standard deviation change scores [F(4, 35) = 6.68, $P < 0.001$, Wilks' $\Lambda = 0.57$] but a significant interaction was not detected [F(4, 35) = 0.82, $P = 0.52$, Wilks' $\Lambda = 0.91$]. Individuals in the mirror feedback group showed smaller limb excursion and step length variability at the end of split-belt exposure compared to BASELINE whereas individuals without feedback demonstrated increased variability [limb excursion: F(1, 38) = 8.01, $P < 0.01$, $f = 0.28$; step length: F(1, 38) = 23.73, $P < 0.001$, $f = 0.55$] (Table 3). Stance time and double support time variability increased during split-belt exposure in both groups but individuals with mirror feedback had significantly smaller changes in variability compared to the no feedback group [stance time: F(1, 38) = 11.92, $P = 0.001$, $f = 0.14$; double support time: F(1, 38) = 17.59, $P < 0.001$, $f = 1.43$] (Table 3).

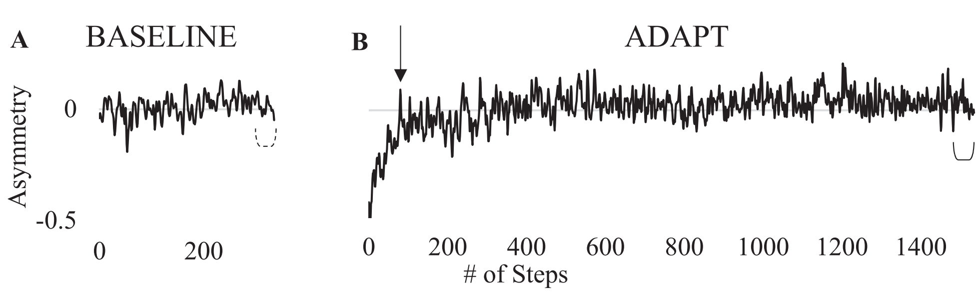

Fig. 1. Gait parameter asymmetry scores plotted across BASELINE (A) and ADAPT (B). A. Plateau range was determined using the last 30 steps of the BASELINE condition (dashed bracket). B. Individuals were considered adapted when they had five consecutive steps within the plateau range (arrow). For example, this participant adapted at stride 109. The standard deviation of the final 30 steps was used to quantify the final adapted pattern (solid bracket).

Table 1
Z-scores of Blom-transformed data for number of steps to adapt step length and double support time asymmetry [means (standard deviation)].

	Mirror	No feedback	*P*
Step length			
ADAPT	−0.07 (1.09)	0.03 (0.71)	0.74
RE-ADAPT	−0.09 (0.86)	0.08 (0.82)	0.56
Double support time			
ADAPT	0.37 (0.73)	−0.38 (1.02)	0.01*
RE-ADAPT	0.08 (1.03)	−0.06 (0.83)	0.68

* Indicate significance at $P < 0.0125$ between groups.

Table 2
Descriptive statistics for number of steps to adapt step length and double support time asymmetries (pre-Blom transformation) [means (standard deviation)].

	Mirror	No feedback
Step length		
ADAPT	246 (226)	218 (176)
RE-ADAPT	26 (18)	29 (17)
Double support time		
ADAPT	252 (154)	132 (163)
RE-ADAPT	27 (19)	24 (15)

3.3. Magnitude of asymmetry

A statistically significant interaction was not detected at the multivariate level [$F(16, 23) = 2.09$, $P = 0.05$, Wilks' $\Lambda = 0.41$] or univariate level for limb excursion [$F(2.14, 81.49) = 0.77$, $P = 0.48$, $f = 0.01$] or step length asymmetry [$F(2.44, 92.68) = 2.15$, $P = 0.11$, $f = 0.01$]. A significant interaction was found at the univariate level for stance time [$F(3.36, 127.74) = 5.23$, $P = 0.001$, $f = 0.03$] and double support time asymmetry [$F(2.13, 81.11) = 5.51$, $P < 0.01$, $f = 0.03$]. Although the multivariate omnibus test was non-significant, with an a priori hypothesis that the mirror feedback would induce behavioral differences based on the condition, the Group × Condition interaction was examined for stance time and double support time asymmetry. Post-hoc decomposition revealed individuals in the mirror feedback group displayed decreased stance time asymmetry during EARLY ($P = 0.001$, $d = 1.10$), MID ($P = 0.001$, $d = 1.12$), and LATE adaptation ($P < 0.001$, $d = 1.29$) (Fig. 2). The mirror feedback group also showed smaller double support time asymmetry during MID ($P = 0.01$, $d = 0.84$) and DE-ADAPT ($P = 0.01$, $d = 0.85$) and smaller stance time asymmetry during RE-ADAPT ($P < 0.001$, $d = 1.35$).

4. Discussion

Corrective feedback can vary in degree of implicit or explicit information provided to the individual (i.e. overtness of the indication that an error exists). The impact of this distinction has been investigated in many domains, such as dynamic balance (Orrell et al., 2006; Shea et al., 2001) and visuomotor adaptation (McDougle et al., 2015; Taylor et al., 2014). Within the realm of split-belt treadmill walking, feedback that directly represents error has been shown to accelerate adaptation (Malone and Bastian, 2010; Roemmich et al., 2016), but does not influence retention (Roemmich et al., 2016). The present investigation investigated the role of frontal plane feedback on motor adaptation and retention using a clinically relevant feedback technique: a mirror view. When provided mirror feedback in the frontal plane, individuals were able to (1) adapt stance time better to the initial split-belt perturbation and maintain reduced stance time asymmetry, evident via decreased asymmetry throughout the split-belt exposure, (2) reinstate their normal walking pattern faster, demonstrated as smaller double support time asymmetry during the first five strides of DE-ADAPT, and (3) converge to a more consistent pattern, observed as decreased variability during the finals strides while walking with the belts split.

Mirror feedback influenced early temporal gait adaptation as individuals were able to reduce their stance time asymmetry within the first five strides of initial split-belt exposure. Individuals with mirror feedback were also able to maintain greater symmetry even into the second split exposure when no feedback was provided. Previously, long-term changes in stance time asymmetry have been absent following split-belt training programs in stroke survivors, despite these asymmetries being present during baseline overground walking (Reisman et al., 2013, 2010b). The results of the current study suggest stance time asymmetry, a gait parameter thought to be unresponsive to manipulation, may be malleable under mirror feedback conditions.

Frontal plane feedback and feedback during split-belt walking have been investigated in isolation from each other (Malone and Bastian, 2010; Roemmich et al., 2016; Willy et al., 2012). Investigations providing sagittal plane feedback observed robust alterations in measures intuitive to the sagittal view, such as step length, whereas methods which implemented frontal plane feedback detected differences in measures such as hip adduction/abduction and pelvic drop (Willy et al., 2012). Stance time asymmetry is perhaps the most perceptible variable from a frontal plane mirror image, which may explain why it responded the most dramatically. Lastly, temporal symmetry has been shown to be much more

Table 3
Descriptive statistics for change scores of the standard deviation of the final 30 steps for all gait parameter asymmetries.

Gait parameter	Condition	Group	Mean	SD
Limb excursion	ADAPT	Mirror	−0.007	0.009
		No feedback	0.002	0.012
	RE-ADAPT	Mirror	−0.004	0.005
		No feedback	0.002	0.010
Stance time	ADAPT	Mirror	0.003	0.004
		No feedback	0.008	0.005
	RE-ADAPT	Mirror	0.004	0.003
		No feedback	0.006	0.005
Step length	ADAPT	Mirror	−0.007	0.010
		No feedback	0.008	0.009
	RE-ADAPT	Mirror	−0.007	0.010
		No feedback	0.006	0.011
Double support time	ADAPT	Mirror	0.010	0.021
		No feedback	0.049	0.036
	RE-ADAPT	Mirror	0.015	0.021
		No feedback	0.050	0.040

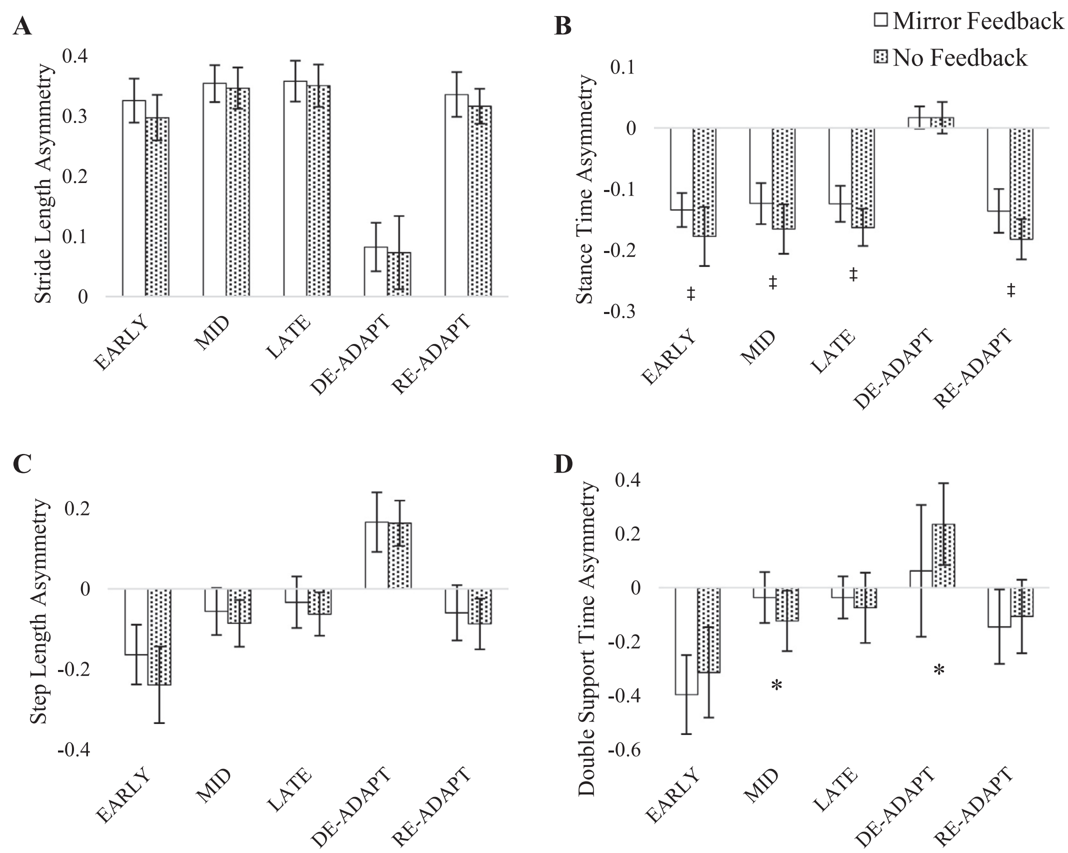

Fig. 2. Gait parameter asymmetry scores for limb excursion (A), stance time (B), step length (C), and double support time (D) averaged over the first five strides of ADAPT (EARLY), the first five strides at the seven-and-a-half-minute mark of ADAPT (MID), the last five strides of ADAPT (LATE), and the first five strides of DE-ADAPT and RE-ADAPT. All figure parts represent mean values with standard deviation error bars. The mirror feedback group is presented as triangles and the no feedback group is presented as squares. * indicates significance at $P \leq 0.01$, ‡ indicates significance at $P \leq 0.001$.

tightly controlled than spatial symmetry (Hoogkamer et al., 2015; Malone and Bastian, 2010), further explaining why stance time asymmetry was affected to a greater extent than limb excursion asymmetry.

Individuals in the mirror feedback group required more steps to adapt their double support time asymmetry during ADAPT and were able to achieve greater double support time symmetry within the first five strides of DE-ADAPT. The mirror feedback group may have spent more time in the adaptation phase and thus became more adept at transitioning between walking patterns. It is also possible individuals in the mirror feedback group displayed greater symmetry during DE-ADAPT because they spent less time walking in the adapted walking pattern during ADAPT. This explanation is unlikely, however, since the mirror feedback group was able to produce similar symmetry during RE-ADAPT compared to the no feedback group.

A novel finding of this study was mirror feedback led to more consistency in the adapted pattern, evident via smaller variability at the end of split-belt exposure compared to the no feedback group. During the initial split-belt perturbation, individuals are unsure how to react or adapt and likely explore variations of gait patterns (Sawers and Hahn, 2013). There are large variations in symmetry from step-to-step as participants try to "solve the puzzle" of asymmetric belt speeds (Malone and Bastian, 2010; Reisman et al., 2009; Roemmich et al., 2016). Over numerous steps, the pattern of adaptation trends back towards symmetry for gait parameters such as step length and double support time asymmetry. In the final 30 steps of split-belt walking, individuals without feedback still had large step-to-step variations, whereas persons who received mirror feedback demonstrated significantly more repeatable steps. These results indicate frontal plane mirror feedback promoted greater regularity and consistency in the adapted gait pattern.

Previously, visual feedback has facilitated faster acquisition of the final adapted pattern (Malone and Bastian, 2010; Roemmich et al., 2016), however mirror feedback had no appreciable effect on the number of steps needed to adapt step length asymmetry. Differences in the number of steps to adapt may be muddled by large within-group variability because, as was the case in both groups, the number of steps needed to adapt ranged from 30 to 1200. Additionally, this temporal measure of adaptation may not be sensitive enough to capture group differences, should they exist.

The ability to quickly adapt may be heavily influenced by other intrinsic factors at an individual level and thus, these differences may confound group comparisons. Seidler et al. synthesized a number of individual factors which may underlie individual differences in sensorimotor adaptive abilities, including genetics, brain connectivity, sensorimotor bias towards a particular type of sensory information, and cognitive features (Seidler et al., 2015). Earlier split-belt work has attempted to extract sensory and cognitive contributions to performance at an individual level (Stone et al., 2018; Torres-Oviedo and Bastian, 2010), but more work is needed to fully assess individual characteristics and their impact on inter-subject variability. Additionally, future work should seek to identify personal characteristics of participants that may influence the way individuals use feedback to adapt to locomotor perturbations. These individual factors may play a role in the effectiveness of mirror feedback on gait adaptation and retention. Lastly, while these results suggest elements of locomotor adaptation, such as stance time asymmetry and gait variability, can be altered acutely, more work is warranted to determine the long term effects of mirror-based feedback and how this can best be implemented in a training program.

Taken together, these results suggest mirror feedback which is implicit in nature promotes a different spatiotemporal adaptation strategy in locomotion. Frontal plane mirror feedback of the participant's lower limbs resulted in improved stance time adaptability, allowed individuals to transition back to their natural double support time pattern faster, and led to a more consistent locomotor pattern. Providing less explicit feedback and allowing individuals to self-prioritize facilitated gait alterations that were previously unexplored.

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Conflict of interest statement

The authors declare no conflicts of interest.

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