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Gait symmetric adaptation: Comparing effects of implicit visual distortion versus split-belt treadmill on aftereffects of adapted step length symmetry

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ABSTRACT

Understanding gait adaptation is essential for rehabilitation, and visual feedback can be used during gait rehabilitation to develop effective gait training. We have previously shown that subjects can adapt spatial aspects of walking to an implicitly imposed distortion of visual feedback of step length. To further investigate the storage benefit of an implicit process engaged in visual feedback distortion, we compared the robustness of aftereffects acquired by visual feedback distortion, versus split-belt treadmill walking. For the visual distortion trial, we implicitly distorted the visual representation of subjects' gait symmetry, whereas for the split-belt trial, the speed ratio of the two belts was gradually adjusted without visual feedback. After adaptation, the visual feedback or the split-belt perturbation was removed while subjects continued walking, and aftereffects of preserved asymmetric pattern were assessed. We found that subjects trained with visual distortion trial retained aftereffects longest. In response to the larger speed ratio of split-belt walking, the subjects showed an increase in the size of aftereffects compared to the smaller speed ratio, but it steeply decreased over time in all the speed ratios tested. In contrast, the visual distortion group showed much slower decreasing rate of aftereffects, which was evidence of longer storage of an adapted gait pattern. Visual distortion adaptation may involve the interaction and integration of the change in motor strategy and implicit process in sensorimotor adaptation. Although it should be clarified more clearly through further studies, the findings of this study suggest that gait control employs distinct adaptive processes during the visual distortion and split-belt walking and also the level of reliance of an implicit process may be greater in the visual distortion adaptation than the split-belt walking adaptation.

1. Introduction

Rebuilding efficient, independent and functional walking is one of the major goals of gait rehabilitation following neurological disorders and injuries (Bastian, 2008; Jette et al., 2005; Roemmich et al., 2014). Movement patterns acquired by gait adaptation bring great importance to rehabilitation (Rode, Pisella, Rossetti, Farnè, & Boisson, 2003). Thus, treadmill-based locomotor training has been utilized as a promising approach that improve gait deficits in individuals with motor impairments such as stroke and Parkinson's disease (Yen, Schmit, Landry, Roth, & Wu, 2012). Especially, restoring symmetric gait is important because deficits in

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spatial gait symmetry place significant limitations on functional mobility such as reduction in gait speed, efficiency of walking, and stability of balance (Hannah, Morrison, & Chapman, 1984; Plotnik, Bartsch, Zeev, Giladi, & Hausdorff, 2013; Sadeghi, Allard, Prince, & Labelle, 2000).

Many studies of split-belt adaptation focused on gait symmetry changes after training healthy or stroke subjects (Bruijn, Van Impe, Duysens, & Swinnen, 2012; Reisman, Block, & Bastian, 2005; Reisman, Wityk, Silver, & Bastian, 2007). For example, Reisman et al. demonstrated that the aftereffects from short-term split-belt walking temporarily induced symmetry in patients who originally showed asymmetric gait patterns (Reisman, Bastian, & Morton, 2010). As another potential way to facilitate improvements in asymmetric gait, we have previously proposed a novel training paradigm, referred to as "visual feedback distortion", involving implementation of visual feedback of step lengths into treadmill walking (Kim & Krebs, 2012; Kim & Mugisha, 2014). In this paradigm, the simple visual feedback consisted of two vertical bars representing subject's right and left step lengths. As subjects walked on a regular treadmill while watching the visual feedback on a computer screen, only one of the vertical bars was distorted without subjects' knowledge of the visual distortion (implicit condition). Prior experiments on healthy subjects (Kim & Krebs, 2012; Kim, Ogilvie, Shimabukuro, Stewart, & Shin, 2015) showed that the subjects spontaneously modulated their gait symmetric pattern away from actual symmetry in response to the distorted visual feedback. Such adaptive response, regarded as visuomotor adaptation in a large sense, occurred without subject awareness and the influence of the adjusted symmetric pattern still remained even after the visual feedback was removed (Kim et al., 2015). The results of our prior studies suggest that the effects of visual feedback distortion on changes in step length symmetry involve an implicit mode of error-driven learning process, which was evidenced by the aftereffects following the visual distortion period. Our prior work has also highlighted that the implicit adaptive processes may better improve the effectiveness of treadmill rehabilitation processes as seen by the more robust aftereffects than that of the conscious change of stepping (Kim et al., 2015).

Understanding locomotor adaptation is essential for effective rehabilitation because aftereffects driven by the adaptation can lead to rehabilitation effects (Rode et al., 2003). In line with this, there has been much interest in the role of explicit and/or implicit processes in motor adaptation (Malone & Bastian, 2010; Mazzoni & Krakauer, 2006; Rendell, Masters, Farrow, & Morris, 2011). Implicit learning process refers to the acquisition of a certain motor pattern without the concurrent acquisition of explicit knowledge about the performance of that pattern. The phenomena of implicit learning have received attention because it has been suggested that implicit processes involved in motor learning are more responsible for improving retention or less prone to forgetting over time than explicit processes (Allen & Reber, 1980; Malone & Bastian, 2010; Rendell et al., 2011). By demonstrating that explicit strategies cannot substitute for implicit adaptation, a previous study on a visuomotor rotation also suggested that the implicit process is nonintentional and automatic (Mazzoni & Krakauer, 2006).

In this study, we extended our prior work of visual feedback distortion to further investigate the storage benefit of the implicit processes engaged in visual feedback distortion (Kim & Krebs, 2012; Kim et al., 2015). To this end, we compared the magnitude of aftereffects of a newly learned motor behavior that was acquired using visual feedback distortion during treadmill walking, versus split-belt treadmill walking under two different belt speed conditions (1:1.14 and 1:2). Although the two different experimental protocols can similarly induce gait changes in step length through error-based adaptation processes as seen by the aftereffects of the gait step symmetry, there are likely to be distinctions between the two protocols as to how different neural structures and sensory modalities are involved in changing and storing spatial gait parameters.

Although both the split-belt locomotor adaptation and the visual distortion adaptation likely lead to new calibrations of feed-forward motor commands as seen by persisting aftereffects, it is obvious that different sensory modalities are involved in the adaptations: one relies on peripheral sensory feedback and the other relies on visual feedback. In addition, there may be overlap of implicit and explicit learning in both ways, but the degree to which an implicit mode of learning process dominates against the other may be different between the two training protocols. Since subjects may be better aware of imposed perturbation in split-belt walking than in visual distortion walking, the level of reliance on implicit learning processes may be greater in the visual distortion trial than in the split-belt trial. Thus, we hypothesized that implicit visual feedback distortion has an advantage in increasing the magnitude of aftereffects of gait symmetry changes compared to split-belt treadmill adaptation. A positive outcome of this study would suggest that implicit visual feedback distortion may be useful for long-term gait rehabilitation as an adapted motor pattern is better retained and decays more slowly.

2. Methods

2.1. Subjects

Twenty-three healthy, adult volunteers (13 male, 10 females), 18–30 years with no visual or physical disability participated in this study. Subjects were not considered for this study if they found it uncomfortable to walk on a split-belt treadmill. Subjects were given a detailed explanation of the study procedure by the researcher before providing their informed consent to participation in this study. All subjects were informed of the physical stress that they would experience during the study and were familiarized with treadmill. All protocols were approved by Institutional Review Board of the Arizona State University. No subjects were presented with information regarding the hypothesis of study.

2.2. Experimental setup

The experimental setup was designed so that all subjects could complete walking experiments without any extraneous training.

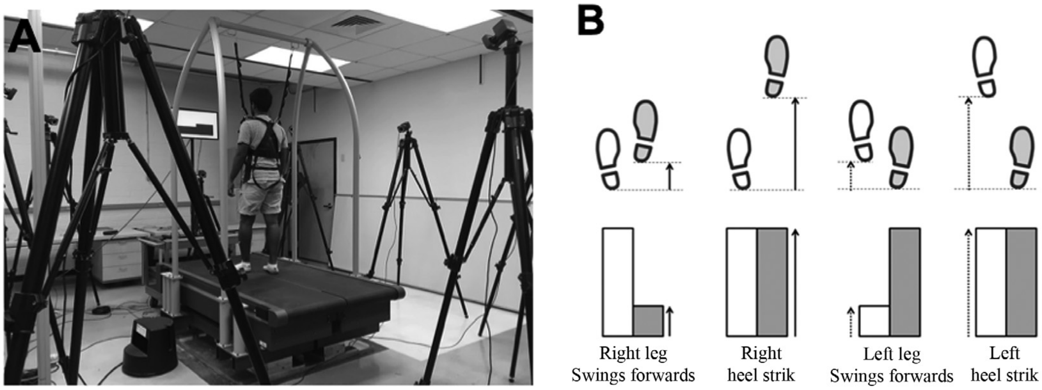

Fig. 1. A: Experimental Setup showing an instrumented treadmill accompanied by a safety harness. Eight infrared cameras were placed in the surrounding perimeter to capture the coordinates of 16 silicon markers attached to the subjects' lower limbs. B: Visual representation of subjects' movement captured using a motion capture system. The range of the right and left step lengths was mapped to the vertical bars. During the swing phase of a leg, the corresponding bar increases proportional to the step length and stops when heel-strike occurs for that leg. For visual distortion, the range of right step length mapped to the visual bar was then gradually distorted.

All walking experiments were performed using a split-belt treadmill (Bertec instrumented dual-belt treadmill, OH, USA) consisting of two separate belts each with its own motor that permitted the speed of each belt to be controlled independently. The treadmill was equipped with a supporting harness to ensure the safety of subjects. All subjects wore a safety harness that would prevent falls while not disturbing the gait (Fig. 1A). A motion capture system (VICON Bonita System, UK) and software (VICON Nexus 2.5, UK) were used to capture subjects' movements during walking for further analysis. The system utilized 8-infrared cameras that precisely detected location of passive reflective markers to track and record subjects' movement pattern. Sixteen markers were attached to lower extremities of the subjects. Marker data were sampled at 200 Hz and then sent to a PC in real-time using a program developed with MATLAB (Mathworks Inc., MA) to graphically represent the subjects' step length measurements on a computer screen.

Each subject participated in both visual distortion (VD) and split-belt (SB) trials. During visual distortion trials, subjects walked on the treadmill with two belts moving at the same speed while looking at the visual feedback display. The real-time visual feedback of step length was provided to subjects on a 23-inch LCD display placed directly in front of the treadmill. The display showed two vertical bar graphs corresponding to the step length for each leg (Fig. 1B). Step length was defined as the distance between two feet during the swing phase. Thus, the height of the corresponding vertical bar increased in real-time, and when a heel strike occurred, the maximum height of the vertical bar remained at its maximum for the whole stance phase until the next swing phase began. The function of the visual feedback system in correspondence with the swing phase is depicted in Fig. 1B. During visual distortion, length of the right bar was distorted in increments of 2% of the actual step-length up to a 114% distortion of their preferred speed (hereinafter referred to as VD114). For example, a 2% distortion of step-length changed the bar height from 100% to 102%. Thus, subjects would perceive their step lengths to be 2% greater than it actually was.

During split-belt trials, subjects walked on the treadmill with two belts moving at different speeds in a gradual manner. In the present study, we performed two different speed ratio conditions (1:1.14 and 1:2). During the moderate split-belt condition, the speed of the belt under the right leg was adjusted in increments of 2% up to 114% (hereinafter referred to as SB114), whereas in the strong split-belt condition, the speed of the belt was adjusted in increments of 15% up to 200% (hereinafter referred to as SB200). No visual feedback was provided during the split-belt adaptation trials.

2.3. Experimental protocol

All subjects were given a 5–10 min habituation period to adjust to walking on the treadmill where they determined their preferred walking speed (PWS), which was used as a reference throughout the experiments. First, subjects began walking at a low speed, and the speed was increased until the subjects found a comfortable walking speed. The speed then rose to a higher level, and was lowered until the subject reached a comfortable speed. If these two speeds were different, they were averaged in order to determine the PWS. During this period, subjects were introduced to the visual feedback system and gained familiarity with its function. Preferred walking speeds ranged from 0.55 to 0.85 m/s with a mean (SD) of 0.72 (0.07) m/s. During split-belt trials, the slow-moving side was set at subjects' preferred speed. In some other studies using split-belt treadmill (Malone & Bastian, 2010; Morehead, Taylor, Parvin, and Ivry 2017a; Reisman, Wityk, Silver, & Bastian, 2009), the fast side belt moved between 1.0 m/s and 2.0 m/s, which was not much different from our experiment.

Experiments were designed to primarily investigate the influence of visual feedback distortion on the modulation of gait spatial pattern (step symmetry) and also to compare its performance with gait modulation under split-belt conditions. Each subject participated in three trials that were at least a day apart: 1) a trial with implicit visual feedback distortion (VD114), 2) a trial with moderate split-belt condition (SB114), and 3) a trial with strong split-belt condition (SB200). The order of experiments was randomized across subjects. Each experiment consisted of a 3-minute control session and a 28-minute main session. The main session was further divided into a 13-minute of *adaptation* (visual distortion or split-belt perturbation) period and a 15-minute of *post-adaptation* (no visual or no speed difference between the two belts) period.

At the beginning of each experiment, subjects participated in the control session. For the visual feedback distortion trial, subjects walked at their PWS while watching the visual feedback display with no distortion. For the split-belt trials, subjects walked at their PWS without any visual feedback provided. The speed of two belts was tied during the control session. After the control session, subjects rested for 15 min before participating in the 28-minute main session.

For the main session of the visual distortion experiment, the average step length was calculated from the control session in order to personalize the visual feedback display. The bar graph's height was adjusted for each subject such that average step length filled 75% of the height of the screen. During the main session of the trials, subjects walked on the treadmill while looking at the visual display for the first 13 min, where the distortion level was increased by increments of 2% after the first two minutes, reaching a total of 114% distortion. Each visual distortion period lasted for 1 min with the maximum distortion rate (114%) sustained for 5 min. Following the distortion period, the visual feedback disappeared from the screen and subjects continued to walk without visual feedback for the rest of the main session (15-minute of post-adaptation). This was considered as an implicit visual distortion condition because subjects were given a visual distortion without knowing that the representation of their step length was being manipulated and they were also completely unaware of the nature of their gait modulation induced by the visual distortion. During the trials, subjects were told only to keep their gaze on the screen and walk comfortably with no specific instructions.

During the main session of the split-belt trials, speed perturbations were applied on the belt under the right leg such that the two belts moved independently at different speeds. Subjects were instructed to look straight ahead and refrain from looking down at the belts while walking so that they could not use visual information to determine belt speeds. Over the first two minutes of the trials, the treadmill was operated in tied-belt condition (two belts moving at the same speed). After then, the slow-moving side was constantly set at subjects' preferred speed and the speed of the right belt (fast-moving side) was adjusted from 100% to 114% in increments of 2% for the moderate split-belt condition trial (SB114), and from 100% to 200% in increments of 15% (except the very first change, which was 10%) for the strong split-belt condition trial (SB200). Each perturbation level lasted for 1 min, with the maximum perturbation size (114% or 200%) sustained for 5 min. Following the perturbation period, speed of the two belts was returned to PWS and subjects walked in this configuration for the rest of the main session (15 min). During the trials, subjects were told only to walk comfortably with no further specific instructions and they were not informed that the treadmill speed was adjusted.

2.4. Data analysis

The primary measure used in this study was step length symmetry. To create the step length symmetry, the ratio (%) between the left step length and the right step length was calculated for each gait cycle by using the following formula: 100 × (left step length − right step length)/(0.5 × (left step length + right step length)). Thus, positive symmetry ratios mean that the left step lengths are longer than the right ones. On the other hand, negative symmetry ratios indicate that the right step lengths are longer than the left ones. Among 23 subjects, 3 subjects did not exhibit modulation in step length symmetry in one or more testing conditions. This was most likely because they were not faithful to constantly looking at the screen. Thus, they were excluded in the data analysis.

The mean and standard deviation (SD) of the symmetry ratios over subsequent 1-minute intervals were calculated per subject to analyze the changes in step length symmetry in the adaptation (13 min) and post-adaptation periods (15 min). For group analysis, new means and SDs of all of the subjects were calculated for each distortion or perturbation level (1-minute interval). Erroneous data or outliers were properly removed. In the visual distortion trial, data was defined erroneous when the step length symmetry was either under −30% or over 30%. Perhaps, these outliers resulted from disruptions in the infrared cameras' abilities to record the location of any marker during the testing period (i.e., sometimes the reflection caused by the material of the shoes worn by the subjects are thought to have caused interference in maker capture). In addition, in all experiments, any value of lying outside of the mean ± 3 SD was considered as an outlier and removed.

First, for the 3-minute control session, we performed two-way repeated measures ANOVA to confirm if the baseline step length symmetry for 3 different trials (VD114, SB114, and SB200) was properly regulated, i.e., the step length symmetry had comparable levels across the 3 trials. The dependent variable was the step length symmetry, whilst the two factors were the experimental conditions (VD114, SB114, or SB200) and times (six 30-second time periods with a total of 3 min).

Next, we performed statistical analysis for the 13-minute adaptation period and the post-adaptation period separately. Since the main goal of the present study was to compare the characteristics regarding the amount of adaptation and aftereffects between the visual distortion and split-belt trials, we first compared the visual distortion trial (VD114) with the moderate split-belt trial (SB114) and also with the strong split-belt trial (SB120). We performed two-way repeated measures ANOVA to examine whether there was a significant effect of different training environments (visual distortion and split-belt walking) on the changes in step length symmetry. The two factors used for this analysis were the experimental conditions (VD114, SB114, or SB200) and the level of perturbation (during the adaptation period) or the time (during the post-adaptation period). In all analyses, Mauchly's test of sphericity was performed to formally test the assumption of sphericity. If the assumption was violated, the degrees-of-freedom was adjusted using the Greenhouse-Geisser correction before calculating the *p*-value. All statistical tests were performed at a significance level of $p < 0.05$. The *p*-values are noted in the main text when they are not otherwise depicted in Figures. Additionally, we performed paired *t*-test between each possible pair of levels or times to examine at which level of perturbation the two different training environments showed significant difference in the changes in step length symmetry.

To investigate differences in the aftereffects among three experimental conditions (VD114, SB114, and SB120) in more details, we looked at three epochs (early de-adaptation, middle de-adaptation, and late de-adaptation) during the post-adaptation period using one-way repeated measures ANOVAs. The period for the first minute during the post-adaptation period was defined as the “the early de-adaptation epoch”, and the period for the last minute during the post-adaptation period was defined as the “the late de-adaptation epoch.” The middle de-adaptation epoch was defined by the period for one minute (7th minute) in the middle of the post-adaptation period. If significant main effect were observed, we performed *post-hoc* analyses using the Bonferroni correction for pairwise comparisons among three conditions.

Note that the aftereffects resulted from the visual distortion and split-belt adaptation trials were shown in the opposite direction. Thus, all the negative sign of aftereffects was changed to a positive sign for all the comparisons we performed.

3. Results

During 3-minute control sessions, changes in step length symmetry were negligible. Statistical analysis using two-way repeated measures ANOVA confirmed that the step length symmetry was not statistically different over time ($F(2.309, 43.871) = 0.909$, $p = 0.423$) and across three experimental conditions ($F(2,38) = 0.829$, $p = 0.444$).

Fig. 2 shows an example of changes in step length symmetry obtained from a subject as a function of time for three different trials (VD114, SB114, and SB200). Since a stride consists of a right and a left step, the number of points (small dots) in the plot indicates the total number of strides during the trial, and each point represents the step length symmetry (%) of each stride. In the visual distortion trial (Fig. 2A), we observed a marked upward trend in the step length symmetry in the first 13 min of the adaptation period. During the post-adaptation period of the following 15 min in the absence of visual feedback, the step length symmetry steadily decreased towards the baseline. In the split-belt trials under two different speed ratios (Fig. 2B and C), we observed the similar upward trend in the adaptation period. Responses during the post-adaptation period appeared to be qualitatively different from those of the visual distortion trial: strong negative aftereffects (the step length symmetry shifted in the opposite direction) were consistently observed in the post-adaptation period of the split-belt adaptation trials.

The trends shown in Fig. 2 were consistently observed in group results (Fig. 3). The main goal of this study was to investigate how the storage benefit of visual distortion walking adaptation differed from the split-belt walking adaptation. Thus, we compared the characteristics regarding the changes in step symmetry between the visual distortion trial (VD114) and the split-belt trials: one with moderate speed ratio (SB114) and the other one with higher speed ratio (SB120). Fig. 3A shows the variability in step length symmetry during the visual distortion trial versus the moderate split-belt trial. We first checked to see how much the VD114 and SB114 groups changed their step symmetry over the course of the adaption period. Statistical analysis using two-way repeated measures ANOVA on the step length symmetry revealed that there was a significant effect of the two different conditions on the changes in step symmetry ($F(3.608, 68.558) = 32.692$ with the Greenhouse-Geisser correction, $p < 0.001$). There was also a significant interaction between the changes in step symmetry and the levels of distortion/perturbation ($F(4.976, 94.538) = 3.985$ with the Greenhouse-Geisser correction, $p < 0.005$). Using paired *t*-test, we then examined at which level of distortion/perturbation (from 0 to 14% with increment of 2%) the two groups showed significant difference in the changes in step symmetry. There were significant differences only over the late periods from 10 to 13 min. *(p = 0.0087, 0.0437, 0.0389, 0.0438, respectively)*.

Since the strong split-belt trial (SB200) applied much higher perturbation (1:2 maximum speed ratio) than the moderate split-belt trial (SB114, 1:1.14 maximum speed ratio), it is not surprising to see that the SB200 group showed larger changes in step symmetry during the adaptation period (Fig. 3B). We repeated the same statistical analysis when comparing data between the VD114 and the SB200 conditions. Statistical analysis using two–way repeated measures ANOVA on the step length symmetry revealed that there was significant effect of the conditions on the changes in step symmetry ($F(2.461, 46.767) = 74.440$ with the Greenhouse-Geisser correction, $p < 0.001$). The comparison using paired *t*-test also showed that the group mean changes in step symmetry for the SB200 condition was significantly greater than those for the VD114 condition over the entire adaptation period except for the initial two minutes *(P = 0.0623, 0.0599, < 0.0001, < 0.0001, < 0.0001, 0.0001, 0.0001, 0.0004, 0.0008, 0.0107, 0.0198, 0.0314, 0.0205, respectively)*.

During the post-adaptation period, the aftereffects resulted from split-belt walking adaptation was represented by step length symmetry in the opposite direction. This indicates that when split-belts returned to baseline (tied belts), it caused the subjects to produce longer right step lengths than the left ones due to the effect of adaptation. In visual distortion trial, however, the effect of visual distortion adaptation was represented by asymmetric step length on the same side. So to fairly compare the data between the two conditions, the negative sign of symmetry ratio values for the split-belt trials were reversed to positive values for further analysis. We were intrigued to observe that the split-belt walking groups deadapted much faster than the visual distortion group. Fig. 3A shows the group mean data in deadaptation, with two-way repeated measures ANOVA results showing a difference in the size of aftereffects between the two conditions ($F(1,19) = 7.713$, $p = 0.012$). Paired *t*-test results also confirmed the differences in the group size of aftereffects over the entire post-adaptation period except for the first two minutes. *(p = 0.8849, 0.2804, 0.0294, 0.0153, 0.0324, 0.0015, 0.0101, 0.0813, 0.0065, 0.0246, 0.0228, 0.0215, 0.0077, 0.0107, 0.0082, respectively)*.

With higher speed ratio applied during adaptation period (SB200 condition), more pronounced aftereffects were observed during the post-adaptation period than the moderate split-belt trial or the visual distortion trial (Fig. 3B). The asymmetry steeply returned toward the baseline and gradually became smaller throughout trial. Statistical analysis using two-way repeated measures ANOVA on the step length symmetry confirmed that the decreased pattern of aftereffects were significantly different between the visual distortion and the strong split-belt condition by showing a significant interaction effect between the time and condition ($F(4.923, 93.543) = 19.837$, with the Greenhouse-Geisser correction, $p < 0.001$). Although further analysis using paired *t*-test showed that the size of deadaptation did not differ between the two conditions except for the initial post-adaptation periods (the first three minutes)

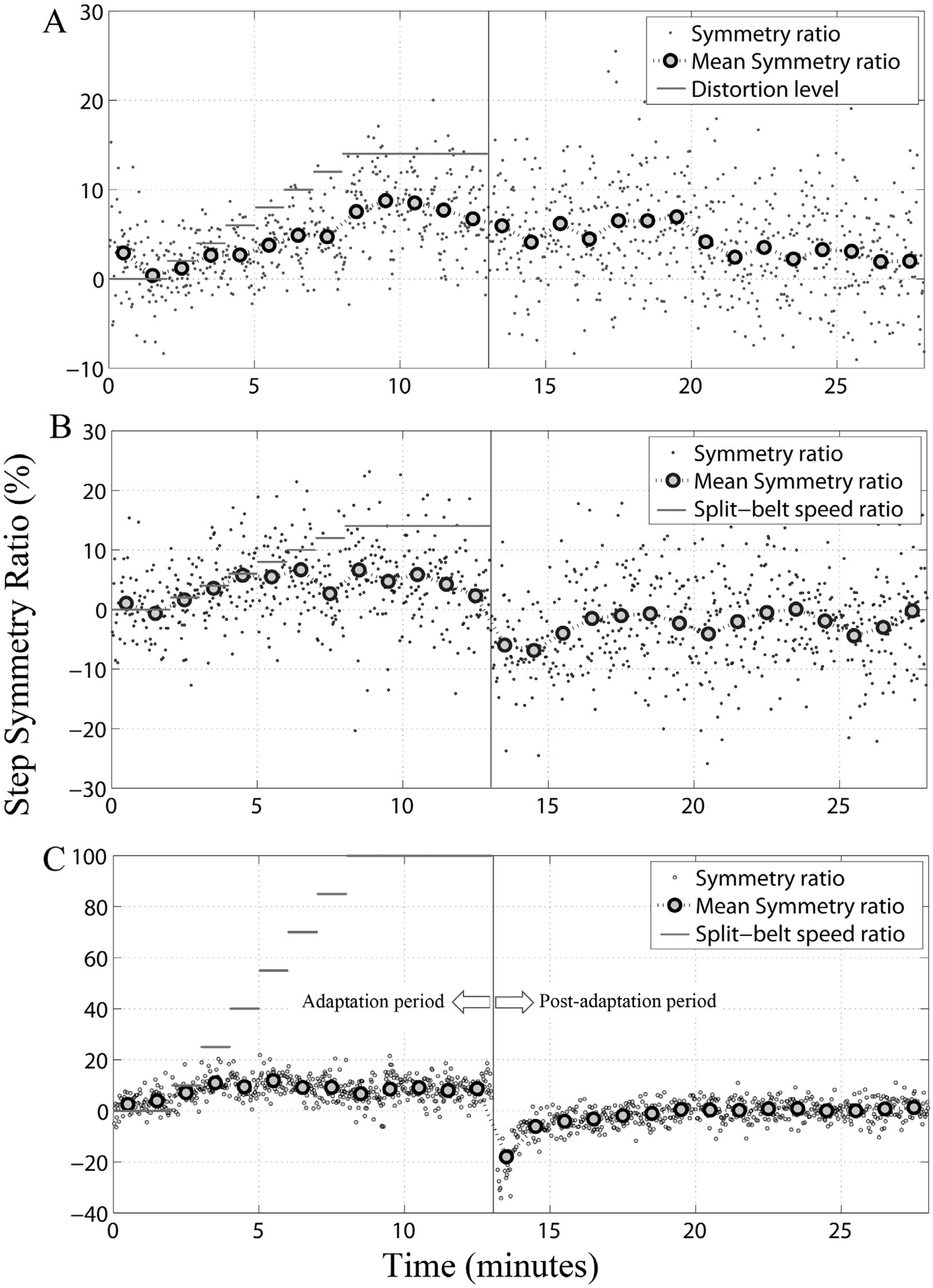

Fig. 2. A: Example of changes in step length symmetry as a function of changes in visual distortion obtained from a subject. B: Example of changes in step length symmetry resulted from a moderate split-belt trial, where belts were split up to 14% ratio (1:1.14 speed ratio). C: Example of changes in step length symmetry resulted from a strong split-belt trial with perturbation up to 1:2 speed ratio. In all trials, visual distortion and split-bet perturbations were only used during the first 13 min (adaptation period). The intermittent horizontal lines indicate distortion or perturbation increments applied during those time periods. The horizontal axis shows time; the vertical axis shows step length symmetry ratio between the left and the right actual step lengths. The circles represent the mean step length symmetry value averaged over 60 s intervals at a given time.

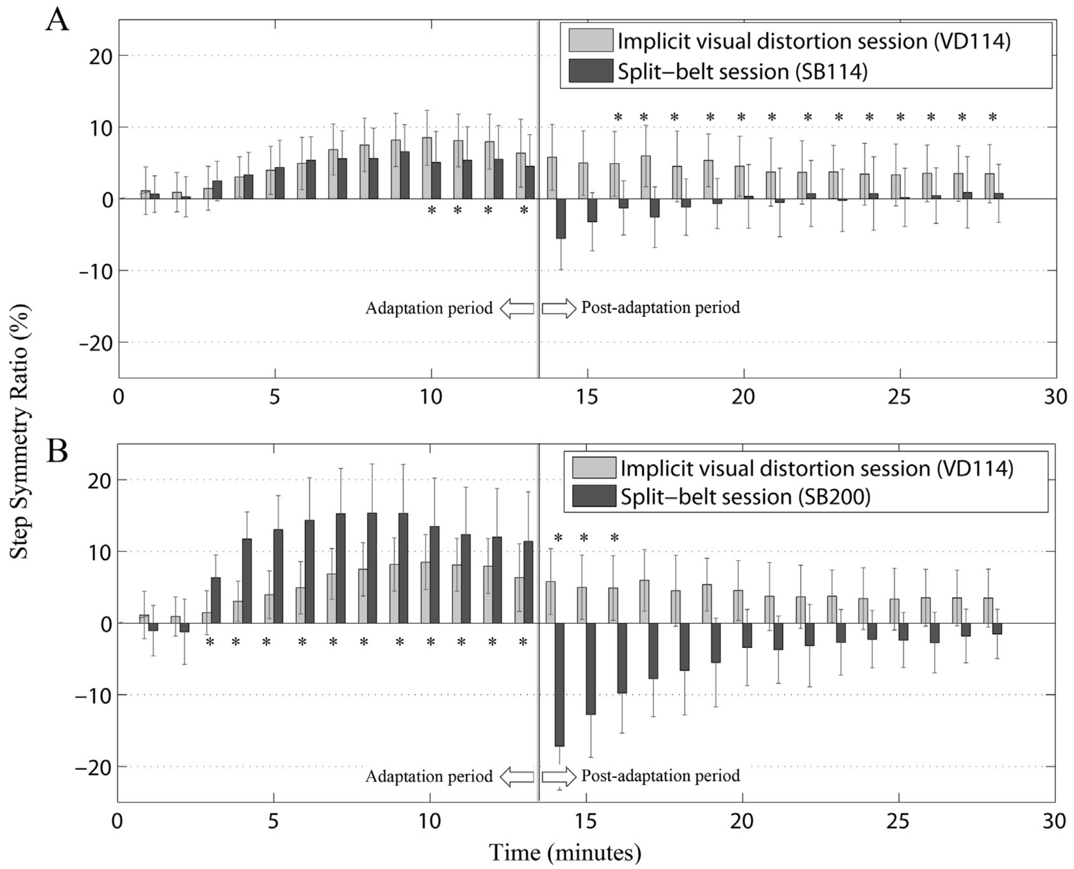

Fig. 3. Group results of averages step length symmetry over time. A: changes in the mean step length symmetry as a function of varying visual distortion and split-belt perturbation averaged across all of the subjects during the implicit visual distortion (VD114) and the moderate split-belt (SB114) conditions. B: changes in the mean step length symmetry during the implicit visual distortion (VD114) and the strong split-belt (SB200) conditions. The vertical lines show the standard deviation among subjects for each level/time. The asterisks (*) were marked at time periods where the induced step symmetry values were shown to be significantly different between different conditions ($p < 0.05$).

(*p* = < *0.0001 0.0001 0.0069 0.2126 0.2609 0.9284 0.3801 0.9953 0.7466 0.4556 0.3918 0.4566 0.5117 0.1518 0.0991, respectively*), the aftereffect for the SB200 condition showed a tendency to continuously decrease; the group means of step symmetry continued to get smaller than those of visual distortion as the trial time ended.

Although group results for de-adaptation behavior are summarized over the entire periods in Fig. 3, we compared the adapted asymmetry (aftereffects) among the three trials during early, middle, and late de-adaptation periods (Fig. 4). Note that the negative sign of asymmetry was changed to a positive sign for split-belt trials. The aftereffects of the adapted asymmetry was evident in all groups in early de-adaptation period, but the aftereffects steeply decreased in both split-belt groups compared with that of visual diction group. One-way repeated ANOVA results showed a difference in the aftereffects size for all three periods ($F(2,38) = 36.16$, $p < 0.001$, $F(2,38) = 5.657$, $p = 0.007$, and $F(2,38) = 5.428$, $p = 0.008$, *respectively)*. Post hoc testing showed that the aftereffects of the adapted asymmetry in the visual distortion group was different from the split-belt groups. In early de-adaptation period, there was no difference in the aftereffect size between visual distortion and moderate split-belt groups (SB114), but much larger magnitude of the aftereffect was observed in strong split-belt group (SB200). In middle and late de-adaptation periods, the aftereffects almost washed out in moderate split-belt group compared with the other two conditions ($p = 0.03$ and $p = 0.025$). Although it did not show significant difference compared with visual distortion group, the magnitude of aftereffects for strong split-belt group continued to decrease in late de-adaptation period.

Fig. 5 shows the changes in the group mean de-adaptation rate during post-adaptation period for the three trials. For this figure, the measured step symmetry data were normalized by an initial aftereffect value. Aftereffects in step length symmetry were less pronounced in the split-belt groups, indicating that the adaptation was stored less prominently. In addition, the percent change in decrease in step length symmetry between the two split-belt conditions seems minimal.

4. Discussions

In this study, we aimed to characterize gait adaptation (learning) and de-adaptation (aftereffects) processes in accordance with

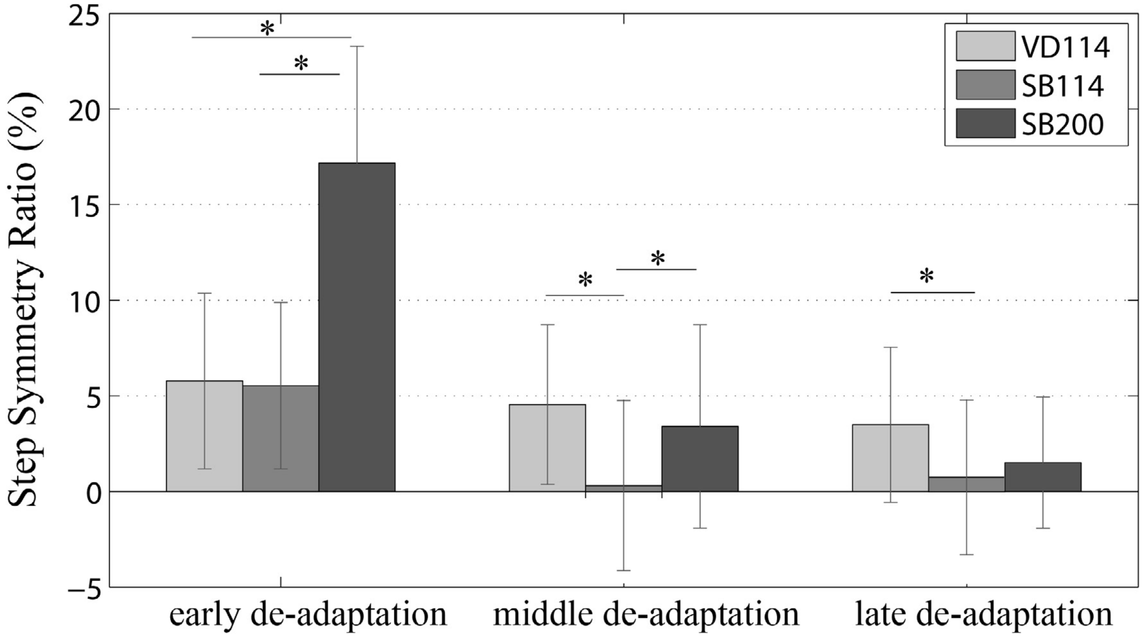

Fig. 4. The aftereffect size expressed as the step length asymmetry retained during the post-adaptation walking period. Visual distortion group took longer to return to the baseline of symmetry than moderate and strong split-belt groups. The asterisks (*) were marked where the retained asymmetry values were shown to be significantly different between different conditions ($p < 0.05$).

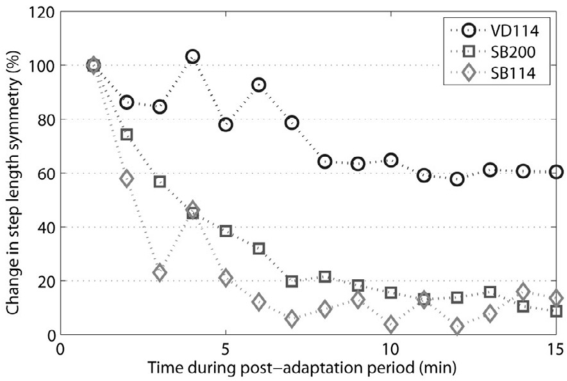

Fig. 5. Change in step length symmetry during post-adaptation period. Group mean step symmetry values were normalized by the initial values (100%). For the data of split-belt conditions, step length symmetries in negative side were converted to positive side. Displaying standard deviation and significant differences were ignored in this plot (refer to Fig. 4).

two different treadmill adaptation conditions. In one condition, subjects walked on a regular treadmill while looking at implicitly imposed distortion of visual feedback of their step length. In the other condition, subjects walked on spit-belts with different belt speeds between the right and left sides without visual feedback. The split-belt walking was tested under two different speed ratios of the split-belts: one was a moderate perturbation (up to 1:1.14) and the other was a strong perturbation (up to 1:2). Our study focused on the effect of the two different adaptation trials on robustness of aftereffects of a learned walking pattern on a short-term basis, which was measured by the extent of asymmetric gait. Our main finding was that there was an advantage of the implicit visual perturbation (visual distortion) over split-belt walking for lasting effects of a newly learned walking pattern.

In response to imposed distortion of visual feedback, subjects spontaneously modulated their spatial gait pattern to compensate for the asymmetric representations of their step lengths (Figs. 1 and 2), which corroborated the results of our prior studies (Kim & Krebs, 2012; Maestas et al., 2018; Tobar, Martinez, Rhouni, & Kim, 2018). In response to the imposed split-belt walking condition, subjects quickly adjusted their spatial gait pattern. Under greater speed ratio of split-belts (strong split-belt condition, SB200), the amount of modulated step symmetry during the initial adaptation period was significantly large compared with that during the visual distortion or the moderate split-belt walking (Fig. 3B). In our trials, the perturbation (either visual distortion or speed difference between two belts) was applied in a gradual manner during the first 13-minute adaptation period. Since the perturbation was applied in a gradual manner, we did not observe a clear pattern of plateau (i.e., step symmetry change is level and stable) during the adaptation period, unlike other studies on split-belt walking adaptation (Bruijn et al., 2012; Malone & Bastian, 2010; Reisman et al., 2009). Interestingly, the amount of the gait asymmetries induced by either the visual distortion or the moderate split-belt perturbation looked similar for the same level of distortion or perturbation (ranging from 100 to 114%) despite the fact that the visual perception or the motor sensory perception might contribute differently to gait control (Fig. 2). After imposing split-belt walking over the first 13 min, the split-belt perturbation was returned to normal (the belts moved at the same speed), and subjects continued to walk for another 15 min. Likewise, in the visual distortion trial, the displaying visual feedback was removed after the adaptation period, and subjects continued to walk. At the initial washout (de-adaptation) period, the strong split-belt condition showed larger aftereffect compared to that in all other conditions (Fig. 3). For the decreasing rate of change in aftereffects, however, there seemed no significant differences between the two split-belt conditions whereas there was significant difference in aftereffects of the adapted gait pattern (step asymmetry) between the visual distortion and the split-belt groups (Figs. 3 and 4).

One of the interesting facts about gait adaptation is that gait patterns can also adapt to visual information about motion or environmental characteristics, not only to physical perturbations (Patla, Niechwiej, Racco, & Goodale, 2002). Such adaptation is regarded as visuomotor adaptation that typically refers to the phenomenon that visually guided motor behavior changes in response to visual feedback. Visuomotor adaptation has been widely studied, with recent studies generally consisting of individuals who make arm-reaching movements towards a target (Morehead, Taylor, Parvin, and Ivry, 2017b; Taylor, Krakauer, & Ivry, 2014). Although numerous studies on visuomotor adaptation have led to many findings about how the brain integrates visual information for the adjustments of motor commands, less is known about how visuomotor adaptation involves human locomotion, partly because, in a typical situation, locomotion is less visually guided than arm control. To gain a greater understating of mechanisms underlying visuomotor adaptation of human locomotion, we have previously proposed a novel gait training paradigm called visual feedback distortion (Kim & Krebs, 2012; Maestas et al., 2018), and have also used it in this study to better understand its effect on short-term storage of adapted motor patterns. Our results showed that subjects spontaneously modulated their gait step pattern in response to the implicitly distorted visual feedback of their step symmetry. Even after the visual feedback was removed, the influence of the adjusted asymmetric gait patterns still remained until the end of trial. During the visual distortion trial, since two belts were constantly tied over the entire trial, the effect of visual distortion adaptation was represented by step asymmetry on the same side, not in the opposite side as seen in the split-belt trial. When we looked at the de-adaptation process between the implicit visual distortion group and the split-belt walking groups, our results surprisingly revealed that the aftereffect magnitude in the implicit visual feedback distortion condition was significantly greater than that of split-belt walking condition (Fig. 5). Over the 15-minute post-adaptation period, the magnitude of aftereffects rapidly decreased down to about 13.6% and 8.8% for moderate (SB114) and strong (SB200) split-belt condition, whereas in visual distortion it slowly decreased and reached a plateau at around 60.4% of its initial value (Fig. 5). This suggests that the adapted motor behavior was stored more prominently in the visual distortion group compared to the split-belt groups on a short-term basis.

Human sensory feedback regarding locomotion arises from many different sensory modalities such as vision and proprioception, and error signals regarding sensory feedback can drive motor adaptation. Although proprioceptive feedback is predominately associated with learning and generalization of limb dynamics, the results of visual distortion trials showed that subjects adapt to visual distortion without altered proprioceptive information, suggesting that error signals regarding visual information can be used for recalibrating the internal model for lower limb control. An extensive literature review points to a critical role of the cerebellum in sensory prediction error-based learning in which the difference between predicted and actual sensory feedback may cause motor adaptation to occur (Huang, Haith, Mazzoni, & Krakauer, 2011; Morehead, Qasim, Crossley, & Ivry, 2015; Morehead, Taylor, Parvin, and Ivry, 2017b; Taylor et al., 2014). Our speculation is that self-walking motion may come from one's innate psychological notion of walking symmetry, and if perception through visual feedback differs from predicted knowledge, gait adaptation could be driven by such sensory discrepancy. Note that the sensory discrepancy incurred by our experiment was task irrelevant because subjects were not required to compensate for the discrepancy. It is also important to note that the gait control during the visual distortion trial involved implicit mode of learning because motor behavior changes were not intended by subjects. Since they were not aware of the imposed distortion during trials, subjects were very unlikely to consciously correct their gait steps.

Our study demonstrated that subjects retain the ability to produce a newly learned gait pattern (asymmetric gait) following a short-term exposure to novel demands like the split-belt treadmill walking and implicit visual distortion. In addition, the results of the present study showed that implicit visual distortion group had longer lasting effects of a newly learned walking pattern than split-belt groups. This finding indicates that the adaptive strategies employed by split-belt treadmill adaption and visual distortion adaptation are distinct from each other. It may be that different neural elements are involved in these processes: neural elements that control interlimb coordination during split-belt walking could be distinct from those that control locomotion during visuomotor task. The differences in these processes may be related to the varying complexity of the parameters, involvement of different sensory modalities, task demands, and/or the level of supraspinal control necessary for adaptation (Musienko et al., 2012). The brain may learn multiple internal models to compensate for different environments or sensorimotor transformations. Thus, separate internal models may be learned for split-belt walking and visual distortion environments (Flanagan et al., 1999), thereby having a different impact on aftereffects of learned patterns.

Why did our visual distortion influence adaptation to have a longer lasting effect (a lower rate of de-adaptation) of the new locomotor pattern? One possibility is that the level of reliance on implicit processes was greater in the visual distortion condition than in the split-belt testing conditions in the current study. Motor learning has been described as the interaction of explicit and implicit processes, and implicit and explicit learning may operate in parallel thereby involving relatively independent processes (Curran & Keele, 1993). Conscious, cognitive, or voluntary control of movements may reflect explicit process, whereas unconscious or unintentional control reflects implicit process in motor learning. Various researchers have proposed that the mechanism underlying the retention benefit of learning is the more reliance on the implicit mode of learning process that may accompany dual-task (e.g., distraction task), and random practice (Allen & Reber, 1980; Malone & Bastian, 2010; Rendell et al., 2011). Higher level of conscious effort tends to demand on working memory and can be beneficial for better performance of the motor task and also for learning a new motor skill (Wulf, Höß, & Prinz, 1998). However, it was suggested that implicit learning, the process by which the knowledge acquired is unavailable to consciousness, may result in longer lasting effects (Kim et al., 2015; Malone & Bastian, 2010; Reber, 1989; Rendell et al., 2011). Previous studies on visuomotor adaptation also suggested that an explicit conscious strategy does not directly impact implicit learning within the motor system, even though it may provide a means to facilitate learning (Mazzoni & Krakauer, 2006). It is not yet clear to us why implicit learning has the advantage of holding on to longer learned motor behaviors. Neuroimaging studies suggest that implicit sequence learning involves an increase in activation in motor regions of the brain, which may help store learned patterns (Hazeltine, Grafton, & Ivry, 1997). Another speculation is that the brain areas underlying implicit learning develop earlier in the period of growth and are therefore more effective at retaining motor learning. In a similar vein, another interesting hypothesis is that consciousness arrives late at the mental level, and that the implicit cognitive processes forms the basis for the emerging conscious process, so they should show greater resistance than should explicit processes (Reber, 1989). However, the exact role of the implicit process in adaptation should be elucidated by future studies.

Another possible explanation for why the visual distortion showed a longer lasting effect is that the participants might have implicitly changed their motor strategy in the visual distortion condition rather than recalibrating their baseline motor commands. Individuals can be prompted to learn movements through strategic methods with environmental cues (Mazzoni & Krakauer, 2006; Morehead et al., 2015), and some environmental cues associated with our task condition might have influenced the participants to rely on user-dependent strategic learning process, resulting in a bias of future movements toward a previously practiced movement even when the perturbation is no longer present (Diedrichsen, White, Newman, & Lally, 2010). Future study with a longer post-adaptation period should examine this.

Although it may be difficult to quantify the extent of the interaction between explicit and implicit actions during motor adaptation, Malone and Bastian (Malone & Bastian, 2010) devised a clever way to examine the interaction of explicit and implicit processes in split-belt adaptation. One group of participants was instructed how to step and given visual feedback of stepping (conscious correction group), and another group performed a dual-task during walking (reduced voluntary control). They found that participants under distraction retained aftereffects longer than conscious correction group and control group as well. This indicates that split-belt walking changes gait patterns by employing both explicit and implicit processes. During split-belt walking, subjects are likely to perceive speed difference of the split-belt, which may require conscious effort and deteriorate the ability to retain aftereffects longer. However, this may not be always the case. A recent study by Hoogkamer et al. (2015) showed that the perception threshold of speed difference of the split-belt is around the 1:1.2 ratio. Thus, in the moderate split-belt condition (1:1.14 at the maximum) used in the current study, subjects might not consciously perceive the perturbing effect and probably implicit process operated more. Despite this, the split-belt walking adaptation led to transient aftereffects of adapted asymmetric patterns compared with the visual distortion adaptation. Overall, our results lend support to the notion that the gait changes induced by visual distortion results in an implicit mode of learning process more than split-belt task environment does. It also stands to reason that the best way to improve storage of learned motor patterns would be to focus on implicit learning strategy.

In a clinical setting, the short-term improvements through repeated practice of the adapted pattern may produce long-term changes in the walking pattern. In order to better understand the utility of locomotor adaptation as rehabilitation interventions, we were interested in understanding how differently adaptive processes driven by two different forms of error-driven adaptation trials affect the storing of a learned motor pattern (retention of a learned pattern). A better rehabilitation program can be considered as the one that enables longer retention of learned motor patterns than others. Quickly learning and storing new walking patterns is also important to help walking remain relatively automatic (Reisman et al., 2009). In this respect, our results suggest that the integration of visual feedback distortion into gait rehabilitation could potentially enhance the outcome of gait therapy with longer retention by providing an implicit mode of learning. Rehabilitation strategies often integrate some form of visual feedback to enhance patient's participation (Hollman, Brey, Robb, Bang, & Kaufman, 2006), and the method of using visual feedback distortion could be one of interactive and effective rehabilitation programs. However, further investigation is needed to determine long-term functional effects of the visual feedback distortion paradigm on overground transfer of an adapted step symmetry.

It is clear that the present study is a first attempt at evaluating the rate of aftereffects (de-adaptation) in two potential therapeutic interventions in gait rehabilitation, which effectively induce changes in spatial gait patterns. In addition, we demonstrated that providing a simple form of visually represented feedback exhibited a clear pattern of visuomotor adaptation occurring in the lower limb and subsequent aftereffects. However, our study is not without limitations. The present data focused only on the spatial aspects in gait; the temporal aspects were not fully explored. Regarding the limitations of this study's experimental protocol, the post-adaptation period was 15 min. It is for sure that the longer period, the better understanding of the longer-term effect. Also, the split-belt trials were not conducted in dual-task environment. Dual-task environment could have reduced some conscious control of split-belt walking, allowing for more an implicit process to play. Then, this could result in longer lasting effect than shown in the current study. The present study did not test how the difference in the size of aftereffect between the two training protocols depends on the walking speed. The amount of adaptation induced by visual distortion and split-belt perturbations may vary with the walking speed (Maestas et al., 2018). These limitations point to the need for further research.

In conclusion, this study examined the aftereffects of a locomotor adaptation in response to two different perturbing environments on a short-term basis; one was visual perturbation displaying distorted visual feedback of step length, and the other was speed perturbation using a split-belt. We found that both tasking environments drove error-driven gait adaptation, but led to different magnitudes of aftereffect of adapted gait patterns. In response to higher perturbation size (speed ratio of the split-belt), the split-belt groups showed an immediate increase in aftereffects. However, the aftereffects steeply decreased over time regardless of the split-belt perturbation size. On the other hand, the visual distortion group showed much slower decreasing rate of aftereffects, which was evidence of longer lasting effects of the adapted motor patterns. These findings suggest that gait control employs distinct adaptive processes during the visual distortion and split-belt walking and also that the level of reliance of an implicit process may be greater in the visual distortion testing condition than the split-belt condition. These results are consistent with several recent studies suggesting the importance of implicit learning context that highly relates to a robust aftereffect of learned motor behavior (Kim et al., 2015; Malone & Bastian, 2010; Mazzoni & Krakauer, 2006; Rendell et al., 2011). Further research involving systematic manipulations of cognitive effort in the split-belt and quantifying the extent of interaction of explicit and implicit control of gait are needed to fully understand the mechanisms underlying the rate of de-adaptation.

Competing interests

The authors declare that they have no competing interests.

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Availability of data and materials

Full data set and software analysis will be provided in case of request.

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