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Quick foot placement adjustments during gait are less accurate in individuals with focal cerebellar lesions

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ABSTRACT

Online gait corrections are frequently used to restore gait stability and prevent falling. They require shorter response times than voluntary movements which suggests that subcortical pathways contribute to the execution of online gait corrections. To evaluate the potential role of the cerebellum in these pathways we tested the hypotheses that online gait corrections would be less accurate in individuals with focal cerebellar damage than in neurologically intact controls and that this difference would be more pronounced for shorter available response times and for short step gait corrections. We projected virtual stepping stones on an instrumented treadmill while some of the approaching stepping stones were shifted forward or backward, requiring participants to adjust their foot placement. Varying the timing of those shifts allowed us to address the effect of available response time on foot placement error. In agreement with our hypothesis, individuals with focal cerebellar lesions were less accurate in adjusting their foot placement in reaction to suddenly shifted stepping stones than neurologically intact controls. However, the cerebellar lesion group's foot placement error did not increase more with decreasing available response distance or for short step versus long step adjustments compared to the control group. Furthermore, foot placement error for the non-shifting stepping stones was also larger in the cerebellar lesion group as compared to the control group. Consequently, the reduced ability to accurately adjust foot placement during walking in individuals with focal cerebellar lesions appears to be a general movement control deficit, which could contribute to increased fall risk.

1. Introduction

Insights into commonly used fall prevention strategies can help to reduce fall prevalence. A frequently used strategy to prevent falling is adjusting foot placement (for review, see [1]). Foot placement adjustments to avoid obstacles have been shown to occur with shorter reaction times than voluntary movements [2]. This suggests that subcortical pathways contribute to the execution of these online gait corrections. Within these subcortical pathways a role for the cerebellum, similar to its role in the control of arm reaching tasks [3], can be expected. This would be in line with observed cerebellar neuronal activity in cats during horizontal ladder walking [4].

Indeed, individuals with degenerative cerebellar diseases display deficits during obstacle avoidance tasks as compared to neurologically intact controls, such as impaired timing of gait events and gaze behavior [5] and excessive foot elevation [6,7]. These deficits are even apparent when obstacles are visible with ample time ahead and alternative foot placement could be pre-planned, rather than modified online. Recently, Fonteyn et al. [8] have shown that obstacle avoidance success rate in individuals with degenerative cerebellar diseases can be improved over ten gait adaptability training sessions on a treadmill instrumented to project virtual stepping stones. However, the ability to adjust gait was not evaluated in relation to available response time, direction of adjustment, nor compared to neurologically intact individuals' performance.

We set out to specifically address the role of the cerebellum in online gait adjustments with varying available response times and directions of foot placement adjustment [9,10] by evaluating foot placement accuracy when walking on virtual stepping stones. With shorter available response time, fast feedback control can be expected to become more important [11]. Similarly, stepping on backward shifted stones (using a short step strategy) requires faster corrections than stepping on forward shifted stones (using a long step strategy). During obstacle avoidance tasks without an imposed correction direction, older adults

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prefer to use a long step strategy [12] and we have shown that imposed short step foot placement adjustments have lower success rates than imposed long step adjustments [9,10]. We focused on individuals with mild cerebellar damage (focal lesions), which typically only slightly impairs unperturbed gait [13], but we anticipated to observe pronounced deficits for online gait corrections, which we expected to depend more on cerebellar function.

We projected virtual stepping stones on a treadmill while some of the approaching stepping stones were shifted forward or backward, requiring adjustment of foot placement. Varying the timing of those shifts allowed us to address the effect of time constraints on foot placement accuracy. We hypothesized that foot placement adjustments would be less accurate in individuals with focal cerebellar damage than in neurologically intact controls and that this difference would be more pronounced for shorter available response times and for backward shifted stepping stones (short step adjustments).

2. Methods

Eleven individuals with stable chronic focal cerebellar lesions after tumor resection at young age [14] and fourteen individuals without a neurological disease history participated in this study. All gave written informed consent form prior to participation in accordance with the Declaration of Helsinki and as approved by the Medical Ethics Committee KU Leuven. Exclusion criteria were inability to walk independently and impaired uncorrected vision.

Participants walked at 3.6 km/h on an instrumented treadmill, equipped with a projector, which allowed us to project virtual stepping stones (C-mill, Motekforce Link, Culemborg, the Netherlands) [9,10,15]. By default, stepping stones were projected according the participant's preferred step length, which was determined before the first experimental block, after participants were habituated to treadmill walking, based on center of pressure trajectories [16]. Additionally, we programmed the software to shift some of the approaching stepping stones forward or backward, requiring participants to adjust their foot placement. For each participant, the size of the stepping stones was adjusted to the length and width of their feet. We gave each participant a standardized instruction in Dutch, which translates best to: "Try to step onto each stepping stone as accurately as you can, note that some of these stones might suddenly move forward or backward when they get closer."

Participants performed four experimental blocks. In the baseline block, the participants had to step onto 60 stepping stones which moved at the treadmill speed of 3.6 km/h, but did not suddenly shift. The three other blocks each consisted of a series of 240 stepping stones of which 40 stones were shifted (32 forward and 8 backward, see Fig. 1 for details) over a distance of 40% of the participant's step length (SL). Forward shifts occurred at different timings: when stepping stones came within a distance of 0.8, 1.0, 1.3 or 2.0 times SL from the participant's center of pressure ("available response distance" [15]). Backward shifts occurred with constant timing at a distance of 1.3·SL. Stepping stones to shift were selected pseudo-randomly and were interleaved with 4–7 non-shifting stepping stones. During each of these three 240 stone blocks, different stepping stones were shifted in different directions with different timing, to prevent participants from anticipating stepping stone shifts based on their memory of an earlier block.

For the analysis, all stones with similar direction and similar available response distance from the three blocks with shifted stones were grouped (resulting in 5 conditions in total). The absolute anterior-posterior distance between the participant's center of pressure and the center of the stepping stone during mid-stance (at 50% of the time between heel strike and toe-off) was used as an outcome parameter for step accuracy, where shorter distances indicating better performance [9,17,18]. We only analyzed anterior-posterior accuracy since all the stepping stone shifts were pure anterior-posterior translations. For each stepping stone in the baseline block and for each shifted stepping stone in the other blocks, we first calculated the distance between the center of the stepping stone and the accompanying mid-stance center of pressure locations. These distances were then corrected for systematic offsets related to potential mismatches between the center of pressure during mid-stance and the center of the foot and between the projector and force treadmill coordinate systems [9,10]. For the baseline block, we used the median offset distance between the center of the stepping stone and the accompanying mid-stance center of pressure location of all 60 stepping stones for this correction. For the shifted stepping stones in the three other blocks, we took the median of this distance for the non-shifting stepping stones 2 and 3 steps ahead of all the shifted stepping stones. The offset-corrected anterior-posterior distance between the center of the stepping stone and the foot was used as our measure of foot placement error [9,10].

We used Student's *t*-test to compare foot placement error for all non-shifting stepping stones between groups. We used a mixed-design ANOVA to evaluate the effects of cerebellar damage and of available response distance (ARD) or direction on foot placement error. We performed Tukey's HSD post-hoc analyses to compare foot placement error at different ARD's.

3. Results

Individuals with focal cerebellar lesions showed larger foot placement errors than neurologically intact controls. For the non-shifting stepping stones foot placement errors were 38 ± 11 mm versus 32 ± 5 mm, respectively ($p = 0.024$; Fig. 2). For the shifted stepping stones the main effect for group was also significant ($p = 0.025$; Fig. 2). Overall, foot placement errors were larger for the individuals with focal cerebellar lesions than for the neurologically intact controls. In both groups foot placement error increased when ARD was shorter (significant main effect for condition: $p < 0.001$; post-hoc comparisons for ARD: all $p < 0.001$, except for ARD = 1.3·SL vs. ARD = 2.0·SL, $p = 0.07$). For both groups the increase in foot placement error with decreasing ARD was similar (non-significant interaction effect: $p = 0.3$). Furthermore, errors for short step adjustments (to backward shifts) were larger than for long step adjustments (to forward shifts) with the same ARD ($p < 0.001$) and this difference was similar between groups.

4. Discussion

Our results confirm that individuals with focal cerebellar lesions show less accurate foot placements. Foot placement error, both for the non-shifting stepping stones and in reaction to suddenly shifted stepping stones, was larger in the cerebellar lesion group than in the control group. However, foot placement error in the cerebellar lesion group did not increase more with decreasing ARD or between long step and short step adjustments than in the control group. Consequently, the reduced ability to accurately adjust foot placement during walking in individuals with focal cerebellar lesions appears to be a general movement control deficit, irrespective of time pressure or direction constraints.

The observed increase in foot placement error with decreasing ARD in both groups is in line with earlier observations of lower obstacle avoidance success rates with decreasing available response time [11,12]. Obstacle avoidance impairments typically seen in older individuals (> 65 years old) become more pronounced for shorter available response times [12] and are related to later and smaller responses in muscle activity [11]. Here, we reject our hypothesis that a similar trend exists for individuals with focal cerebellar lesions. Furthermore, short step adjustments were performed less accurately than long step adjustments, in-line with earlier observations for young and older individuals [9,10], but the differences between directions were independent of cerebellar damage. Interestingly, while earlier data indicate that short step adjustments are more difficult, Fonteyn et al. [8]