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VISUOMOTOR ADAPTATION OF VOLUNTARY STEP INITIATION IN OLDER ADULTS

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Abstract

It has been suggested that feedforward planning of gait and posture is diminished in older adults. Motor adaptation is one mechanism by which feedforward commands can be updated or fine-tuned. Thus, if feedforward mechanisms are diminished in older adults, motor adaptation is also likely to be limited. The purpose of the study was to compare the ability of healthy older versus young adults in generating a voluntary stepping motor adaptation in response to a novel visual sensory perturbation. We recorded stepping movements from 18 healthy older and 18 young adults during baseline and adaptation stepping blocks. During baseline, the stepping target remained stationary; in adaptation, a visual perturbation was introduced by shifting the target laterally during mid-step. We compared adaptation between groups, measured by improvements in endpoint accuracy and movement duration. Older adults adapted stepping accuracy similarly to young adults (accuracy improvement: $29.7 \pm 27.6\%$ vs. $37.3 \pm 22.9\%$, older vs. young group respectively, $p = 0.375$), but showed significant slowness during movement. Thus older adults were able to achieve accuracy levels nearly equivalent to younger adults, but only at the expense of movement speed, at least during the early adaptation period (movement duration: 1143.7 ± 170.6 ms vs. 956.0 ± 74.6 ms, $p < 0.001$). With practice, however, they were able to reduce movement times and gain speed and accuracy to levels similar to young adults. These findings suggest older adults may retain the ability for stepping adaptations to environmental changes or novel demands, given sufficient practice.

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Keywords

motor learning; elderly; gait; balance; falls

INTRODUCTION

Motor adaptation can be defined as the process of making feedforward modifications or adjustments to already well-learned movements or motor skills that occurs over a relatively short period of trial-and-error practice during exposure to a novel, perturbing context or environment [1]. The brain circuitry that computes the feedforward motor commands based on knowledge of the desired movement as well as an internal representation of the body, its dynamics and the environment with which it interacts [2–4] is referred as an internal model [4]. It is theorized that motor adaptation serves to fine-tune or update the internal model for a given motor task [4,5]. Visuomotor adaptation specifically refers to motor adaptation driven by changes in visuospatial perception. It provides humans the adaptability and flexibility to quickly accommodate changes in the visual environment. For gait, quickly learning and storing a new walking pattern helps keep walking relatively “automatic”, allowing attention to be focused on potentially more important events, such as monitoring traffic or avoiding an obstacle.

Studies have demonstrated that older adults have slower velocities and take shorter steps during walking [6,7]. They also show delays in reorienting the center of mass when turning [8] and poor anticipatory postural adjustments when attempting to counter inertial perturbations induced by their own moving limbs [9,10]. Impaired interlimb coordination and reduced anticipatory muscle activation patterns in the legs during gait initiation are also characteristic of this population [11,12]. Based on these findings, some have hypothesized that older adults have an impaired ability to generate predictive feedforward adjustments important for posture and gait [11–13]. However, it is not clear whether the observed deficits are truly attributable to poor feedforward planning or whether they reflect only motor execution deficits. For example, reduced force-generating capacity, decreased muscle power and flexibility, reduced somatosensation or cognitive or psychological issues (e.g., fear of falling, etc.) could explain the deficits observed without a problem in feedforward control. One ideal test of the development of new feedforward commands is motor adaptation, since motor adaptation relies on the generation of new feedforward commands via repeated task practice to produce the adapted movement pattern. Yet to date, no study has examined the ability of healthy older adults to generate a motor adaptation of voluntary stepping movements based on trial-and-error practice. If older adults are capable of adapting stepping movements, it would suggest that these individuals retain the ability to benefit from trial-and-error practice based interventions and, therefore, that the types of impairments described above might be correctable if specific rehabilitation interventions based on motor learning are applied.

The purpose of this study was to examine the ability of healthy older adults to adapt voluntary stepping movements to a novel sensory perturbation. We asked the question: can healthy older adults adapt stepping to the same extent and rate as young adults? We hypothesized that older subjects would adapt more slowly than young subjects and show evidence of impaired predictive, feedforward motor adaptation mechanisms for posture and locomotion.

METHODS

Thirty-six healthy adults, 18 young (mean age $\pm$ 1 SD, 26 ± 3.7 years, range 22–33; 13 females) and 18 older (72 ± 4.2 years, range 66–80; 12 females), participated in the study. This sample size was based on our previous work with healthy older adults using a similar paradigm [14].

Older adults were recruited through advertisements posted at local senior centers, the YMCA and a bicycling club. Subjects were excluded if they had any history of serious orthopedic, cardiovascular, or neurologic diseases or dysfunctions, any history of falls, or any pain at the time of testing. Older adults were required to meet additional inclusion and exclusion criteria and to pass a brief clinical examination (see Tables 1 and 2). Prior to participation, subjects gave informed consent and the study was approved by the local ethics committee.

We compared stepping movements between young and older subjects as they adapted to a predictable shift of a visual target during a volitional step initiation task. At the start of each trial, subjects stood quietly with arms crossed and feet approximately pelvis-width apart (foot placement was marked by boundary lines on the floor). Underneath the left foot was a force plate (AMTI, Watertown, MA; see Figure 1a). Approximately 1–3 seconds (time varied randomly trial-to-trial) after an auditory “ready” cue, the visual target, a red circular laser light (approximately 2 cm diameter), was illuminated on the floor and acted as the “go” cue. Subjects were instructed to step with the right leg “so that you aim the center of your foot on the center of the target. Step as fast and accurately as you can”. During each trial, subjects were required to step first with the right leg (the stepping leg) and then to advance the left leg (the supporting leg) forward to the same location.

In *baseline* trials, the target was located directly in front of, and at a distance of 40% of body height away from the stepping leg. In *adaptation* trials, the target first appeared for 550 ms in this position, but was replaced by a second target located at a distance of 10% of body height either to the right or the left of the original location. The second target illuminated at exactly the same time the original target light extinguished, thus it appeared to subjects as though a single target shifted in space from one location to another. The visual target shift provided the sensory perturbation. The target shift time of 550 ms was chosen because we previously showed that both young and older adults will typically have already begun their stepping response toward the initial target by this time [14]. A block of 20 baseline stepping trials was completed, followed by a block of 30 adaptation trials toward either the right or the left. Target shift direction to the right or left was counterbalanced between subjects such that half the subjects in each group ($n=9$) performed the adaptation block with the target shift to the right; the other half performed the adaptation with the target shift to the left. Prior to data collection, subjects had several practice trials to become accustomed to the task and viewing the laser with and without the foot on the target. Subjects were not told when the adaptation block would start, where the target would shift, or whether target shifts would appear in random or blocked order.

Position data were collected using the Optotrak system (Northern Digital, Inc., Waterloo, ON). Three infrared-emitting markers, placed on the fifth metatarsal head, the lateral base of the calcaneus and the lateral malleolus of the right foot, measured movement in three dimensions. Eight footswitches (Motion Lab Systems, Inc., Baton Rouge, LA) were placed on the soles of the shoes; two at the most distal edge of the heel and two at the first and fifth metatarsophalangeal joints, bilaterally, to record the timing of footfalls. Kinematic data were collected at 100 Hz; footswitch data and ground reaction forces were collected at 1000 Hz and time-synchronized with the kinematics.

All analyses were conducted using custom MATLAB (Mathworks, Natick, MA) software. Offline, foot position and force data were low-pass filtered at 10 Hz. Stepping accuracy and movement phase durations were measured for each step trial. Accuracy was quantified using the medial / lateral error in stepping foot endpoint position, which was determined by comparing foot marker locations at the end of each stepping trial to their locations during calibration trials. We identified three movement phases within each trial: response time, weight transfer, and stepping execution phases (see Figure 1b). Response time encompassed the time from initial target illumination to onset of the first decrease in the vertical force under the

supporting leg to below 5% of the mean vertical force during quiet standing. Weight transfer was the time from the end of response time phase to onset of heel-off on the stepping leg. Stepping execution was the time from the end of weight transfer phase to subsequent initial contact of the stepping leg onto the floor. The sum of these three movement phases was considered the total stepping movement duration.

To quantify the ability to adapt to the novel target shift, we measured both accuracy and movement (and movement phase) durations at three key time periods of each testing session: late baseline, early adaptation and late adaptation. The late baseline period was defined as the last three trials of the baseline block; early and late adaptation periods were the first three and last three trials of the adaptation block, respectively.

Statistical comparisons were made using SAS/STAT software (SAS Inc., Cary, NC). A two-way (group $\times$ time period) mixed model ANOVA with repeated measures was used to compare differences in each variable between groups over the three time periods. When the ANOVA was significant, post-hoc analyses were performed using Tukey's HSD test.

RESULTS

There were no differences in height ($p=0.6$) or body mass ($p=0.8$) between young and older groups. As expected, after several trials of the predictable target shift, all subjects generally demonstrated a consistent pattern of reduced lateral errors and shorter movement times.

Figure 2a shows lateral stepping errors on a trial-by-trial basis averaged over all subjects in both groups. As expected, lateral stepping errors increased dramatically in both groups during early adaptation. However, accuracy improved over the course of adaptation such that lateral errors were relatively low by the late adaptation period. Figure 2b demonstrates the group results for lateral stepping errors across the late baseline, early adaptation and late adaptation periods. There was a significant effect of testing period ($p<0.001$); lateral errors were significantly increased during early adaptation (post-hoc $p<0.001$), but became no different from baseline by late adaptation. There were no differences between the young and older groups ($p=0.99$) and no interactions ($p=0.44$).

Movement durations (see Figure 3) showed a different trend. Total movement durations on a trial-by-trial basis (Fig. 3a) show overall the older group took a longer time to complete each stepping trial. In addition, older adults appeared to require additional time during early adaptation, but were able to improve movement times over the course of adaptation back toward baseline levels. Young adults, on the other hand, appeared not to require any additional time during the early adaptation period, and therefore showed fairly constant movement times over all baseline and adaptation trials. Statistically, the older group had longer (slower) movement times overall (group effect, $p<0.001$; Fig. 3b). There were also an effect of period ($p=0.002$) and a group $\times$ period interaction ($p=0.047$), such that movement times in the older group during early adaptation were significantly greater than any other period for the older group (post-hoc both, $p<0.05$) and any period for the young group (post-hoc all, $p<0.01$).

To determine which phase(s) of the stepping movements differed most significantly between older and young groups, we compared the response time, weight transfer and stepping execution phase durations. For the response time phase (Fig. 3c), older adults took longer overall (group effect, $p=0.004$), early adaptation was longer (period effect, $p<0.001$), and there was a group $\times$ testing period interaction ($p=0.005$). Response times in older adults during early adaptation were significantly greater than any other period within the older group (post-hoc both, $p<0.001$) and any period for the young group (post-hoc all, $p<0.05$). Weight transfer phase durations (Fig. 3d) also showed a main effect of period ($p=0.002$), with the late adaptation period being faster than either the late baseline or late adaptation periods (post-hoc, both

$p < 0.01$). There were no group differences in weight transfer durations, but there was an interaction ($p = 0.022$): the weight transfer duration in the older group was shorter during late adaptation than either late baseline (post-hoc, $p = 0.003$) or early adaptation (post-hoc, $p = 0.001$). For the stepping execution phase duration (Fig. 3e), older adults took significantly longer compared to younger adults ($p = 0.002$). There were no significant differences across periods ($p = 0.074$) or any interactions ($p = 0.89$).

DISCUSSION

We compared stepping motor adaptations in young and older adults using both spatial (lateral stepping error) and temporal (movement duration) measurements. For the spatial component, older adults showed rapid and equivalent adaptation compared to young adults, in terms of both the rate and magnitude. However, older adults had significant deficits in the temporal component. Our results suggest that older adults may only be able to achieve the same rapid rate of adaptation of movement endpoint accuracy through a compensatory mechanism of speed reduction. This is the first study to quantify the ability of healthy older adults to adapt voluntary stepping to a novel sensory perturbation.

It is important to consider these results in the context of the well-known speed-accuracy tradeoff [17]. The shift of the target produced significant movement errors in both young and older adults during early adaptation; these were rapidly reduced down to pre-adaptation levels (Fig. 3b). Young subjects showed no speed decrements at any point during the adaptation to the shift in target position. In contrast, older adults demonstrated a clear increase in movement durations during early adaptation, in addition to increased movement errors. Eventually total movement durations dropped down to pre-adaptation levels (Fig. 3b), but the initial increase suggests these subjects may have only been able to achieve accuracy levels similar to young adults by reducing speed during early adaptation.

The assessment of each movement phase duration provides further insight. Total movement times were always increased in the older adults, by approximately 100 ms on average in the late baseline and late adaptation periods (Fig. 3b). This is attributed primarily to slowness during stepping execution (Fig. 3e) since they took, on average, about 70 ms longer to complete stepping compared to young adults. Movement execution prolongation is a common finding in older adults and has been called an indicator of increased reliance on slower feedback-mediated processes [18]. The slowness during stepping execution can account for most of the offset between groups in total movement duration, but it does not explain the sharp increase during early adaptation. For this, we must look to the response time data (Fig. 3c). There was a significant increase in response time durations during early adaptation (returning to near-baseline levels by the end of adaptation) of approximately 50 ms in the older adults, accounting for about 2/3 of the increase in total movement time in this group over the same time period. The response time phase encompasses the time required for sensory stimulus detection and processing, cognitive planning and movement planning, all before movement initiation. Response time increases have been shown in older adults during multitask conditions [19], conditions with a heavy cognitive demand [20] and complex conditions, particularly when inhibition of responses to irrelevant stimuli is required [21]. In this study, shifting the visual target may have constituted a significant increase in complexity or cognitive load, at least initially. Nevertheless, the fact that by the end of adaptation older subjects were able to reduce response time durations back to pre-adaptation levels indicates older adults can improve with practice and older adults can achieve response time durations nearly as short as young adults.

Overall, the increase in movement times associated with the initial adaptation of stepping movements in older adults arises largely from response time delays and less so from prolongation of either weight transfer or stepping execution phases. Although we did see

decreased weight transfer phase durations in late adaptation in the older adults, there were no changes between baseline and early adaptation so this could not account for the increased total movement time in older adults during the critical early adaptation period.

The current study has some limitations worthy of mention. First, we only recruited older adults who were relatively healthy and engaged in regular physical activity. Thus our selection bias limits the generalizability of our results to only rather fit older adults. Second, this study only investigates motor adaptation within a single session and cannot address retention or long-term learning. It will be important for future studies to compare motor adaptation across different age cohorts, between sedentary and physically-active older adult groups, and over longer time periods.

In conclusion, the current study shows that healthy older adults can adapt voluntary stepping in response to a novel visual perturbation when given enough time. These findings suggest that older adults can adjust movement patterns over even short bouts of practice, and therefore may benefit from rehabilitation and prevention interventions to improve postural and stepping deficits common in this population. However, limitations in movement speed should be considered.

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Figure 1.

(a) Overhead view of paradigm. The gray rectangle indicates the force plate. Horizontal arrows indicate the direction of target shift in adaptation trials. (b) Ground reaction forces and foot trajectories from two exemplar young individuals. Vertical arrows indicate the direction of ground reaction forces and foot marker trajectories with respect to body orientation, e.g., R=right. Adaptation data are from the late adaptation period. Solid vertical lines delineate the boundaries of the response time (RTP), weight transfer (WTP) and step execution (SEP) phases. Dashed vertical lines indicate the time of the target shift.

Figure 2.

(a) Average stepping endpoint errors. Each data point represents the lateral stepping endpoint error for that trial, averaged over all subjects in each group. The last ten baseline and all adaptation trials are shown for each group. (b) Average lateral stepping endpoint errors across the three key time periods for both groups: late baseline (last three baseline trials), early adaptation (first three adaptation trials), and late adaptation (last three adaptation trials). Because distances of target shifts were normalized to subject height, errors are presented as a percentage of the total distance between targets. Positive numbers represent leftward errors during baseline and undershooting errors during adaptation. Error bars, ± 1 SEM. Asterisks indicate specific significant post-hoc differences for the main effect of time period.

Figure 3.

(a) Average movement durations. Each data point represents the total movement duration for that trial, averaged over all subjects in each group. The last ten baseline and all adaptation trials are shown for each group. (b) Average total movement durations across the three key time periods (same as Figure 2) for both groups. (c–e) Same for response time phase (c), weight transfer phase (d), and stepping execution phase (e) durations. Error bars, ± 1 SEM. Asterisks show various specific significant differences from the interaction effect post-hoc (b, c), the time period effect post-hoc (d), or the group main effect (e).

Table 1

Full inclusion and exclusion criteria for the older adult group.

Inclusion Criteria	Exclusion Criteria
<ul style="list-style-type: none"> • Independent with all activities of daily living • Independent in community • Engaged in some form of regular (≥ 2 days/week) physical activity • Able to see visual targets and perform the baseline stepping task • Pass a brief clinical exam (see Table 2) 	<ul style="list-style-type: none"> • Use of any walking mobility aid • Any current or significant history of orthopedic, cardiovascular, neurologic or other medical disease or dysfunction • Any falls within past year • Any chronic pain or any pain at time of testing

Table 2

Components of the brief clinical examination for older adults.

	Test	Required Score
Strength	Manual muscle testing ^a	≥ 4 (on a 0–5 scale) on 3 of 3 attempts
Cutaneous Sensation	Semmes-Weinstein monofilaments ^b	Threshold, handle mark ≤ 3.84
Proprioception	Side-to-side position matching test ^c	Discrepancy < 5° on 5 of 5 attempts
Vision	Self-reported acuity	20/40 or better with corrective lenses
Balance	Maintain tandem stance with eyes closed ≥ 30 seconds	Able to perform on ≥ 1 of 2 attempts

^a A 'break' test using manual resistance; force levels applied are rated. Values of 4 or 5 indicate good or normal strength [15].

^b Monofilaments (Wood Dale, IL) were applied to bilateral feet and lower legs to determine the threshold for detection. Handle mark ratings, determined by filament thickness and force, of 3.84 or better (lower) on the lower leg or dorsum of the foot is considered the borderline between normal and diminished touch sensation [16].

^c This test assesses limb position sense (here, bilateral ankles and knees). A joint is placed at a particular angular position and the subject is asked to move the opposite limb to the identical position.