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Effect of a Vocal Choice Reaction Time Task on the Kinematics of the First Recovery Step after a Sudden Underfoot Perturbation during Gait

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Abstract

Thirty-two healthy young adults (15 women) were tested for their ability to maintain their comfortable step pattern following an unpredictable underfoot perturbation in the presence and absence of a concurrent vocal choice reaction time task. Custom instrumented shoes were used to randomly deliver an unexpected medial or lateral forefoot perturbation that inverted the mid-foot an average of 10 degrees or everted the midfoot an average of 9 degrees during one stance phase of a gait trial. Medial and lateral perturbations were randomized between left and right feet in 12 of 30 gait trials. The results of the repeated measures analyses of variance show that, compared to the step parameters of unperturbed gait, the administration of the unexpected underfoot perturbation did not significantly lead to alterations in the step length or width of the first recovery step. In addition, the simultaneous administration of a vocal choice reaction time task with the underfoot perturbation did not significantly affect the kinematics of the first recovery step. We conclude that in young healthy adults an unexpected 9–10 degree underfoot perturbation, with or without a vocal reaction time task, will not affect their recovery step kinematics when walking at a comfortable gait speed.

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CONFLICT OF INTEREST STATEMENT

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INTRODUCTION

Stepping unexpectedly on a discrete raised object can destabilize gait to a significant degree, even in young adults¹. Since natural gait surfaces are typically uneven, such occurrences are not uncommon. As such, balance during walking is often challenged and trips as well as slips have been implicated in the causation of the majority of falls².

Walking safely across uneven terrain requires an individual to be attentive and adaptively responsive. The connection between attention and gait on flat surfaces has been demonstrated in numerous studies. One such study³ used a walking adaptation of trail-making, a validated marker of executive function, of which attention is a specific example⁴. Performance times were found to be slower in the cognitively more challenging “numbers +letters” trail than in its “numbers-only” counterpart. Also, gait derangements have been consistently reported in pathological states characterized by the deterioration of attention. Thus, children suffering from attention-deficit hyperactivity disorder walk with greater stride-to-stride variability and this deficit is alleviated by treatment with attention-enhancing medication⁵. In demented older adults, slower gait speed and shorter step length have been documented, in comparison with age-matched healthy controls⁶.

Perhaps the most common investigative approach to the question of the interplay between attention and gait is the dual-task experimental paradigm in which attentional resources are challenged by requiring the simultaneous performance of an attention-demanding task during gait⁷. Since attention is a finite resource, interference would be expected to occur between both tasks if gait demanded additional attention, the so-called dual-task cost or decrement^{7,8,9}. In everyday life, it is common for human beings to engage in multitasking, such as chatting and watching out for traffic while crossing a street with a friend. Indeed, the seminal studies of Lundin-Olson and colleagues showed that talking, for example, does interfere with walking¹⁰. In general, the more complex the gait task, the greater the demand on attentional resources^{11,12}.

In dual task studies, participants have usually walked on a flat regular or instrumented walkway while performing such tasks as carrying on a conversation¹⁰, responding to auditory or visual stimuli¹³, reciting animal names¹⁴, spelling¹⁵ or counting backwards¹⁶. To the extent that we are aware, only one method, namely obstacle negotiation, has been used to complicate the gait task in the presence of divided attention^{7,17–19}. However, with the exception of Chen et al., the obstacles were fixed in position and foreseeable. In the present study, we report the use of a novel method²⁰ for challenging gait which has the added merit of unpredictability.

The purposes of the investigation were to examine the stepping responses of young adults to an unexpected gait challenge posed by a sudden underfoot perturbation and to better understand the interaction between the performance of such a complex gait task and simultaneous auditory distraction posed in the form of a vocal choice reaction task. It was hypothesized that the greater attentional demand of controlling gait in a challenging dual-task situation would significantly affect recovery step kinematics following the underfoot

perturbation, as well as the vocal choice reaction during that recovery, compared to the case when attention is not divided.

SUBJECTS AND METHODS

Subjects

Thirty-two healthy young subjects (17 males, 15 females; age: 22.1 ± 3.3 years; height: 172.9 ± 7.5 cm; weight: 72.6 ± 17.5 kg; body mass index: 24.1 ± 4.7) were recruited through the University of Michigan Clinical Studies Volunteer Network. They were screened by telephone for neurological or musculoskeletal disorders such as stroke, peripheral neuropathy, head trauma, persistent dizziness, visual impairment not correctible with prescription glasses, diabetes mellitus, flaring osteoarthritis, amputation, spinal surgery, muscle and bone mineral disease. Pregnant female volunteers were also excluded.

Before the walking trials, a written informed consent to participate was obtained and a focused physical examination of the neuromuscular system was performed. Peripheral neurological integrity was clinically evaluated as described by Richardson²¹. Outstretched upper extremities were assessed for pronator drift. Unipedal stance and Romberg tests were also performed.

For safety during the walking trials, subjects wore a harness attached to a track in the ceiling. In addition, a staff member walked alongside as spotter. Approval to use human subjects was obtained from the University of Michigan Institutional Review Board (HUM 00016379).

Perturbing Shoes

Participants wore specially designed footwear²⁰ (Fig. 1A). Nike sandals (ACG Rayong) were modified by an orthotist who replaced the sole with a customized sole. Hidden in a recess under the intermetatarsal joints of the forefoot were two retractable aluminum flaps, each 18.4 mm high, centered 20 mm on either side of the foot axis. Each flap was connected via a flexible shaft to a low-voltage DC linear actuator (Firgelli, Inc., PQ-12) housed in a heel recess. In any particular swing phase, either flap could be remotely triggered to emerge and deploy in a quasi-parasagittal plane during the swing phase of the gait cycle within 400 ms. The trigger mechanism was controlled by a custom-developed C++ program (Visual Studio 2008, Microsoft, Inc., Redmond) which uses Optotrak Application Programming Interface (Northern Digital Inc., Waterloo, Canada).

When the subject stepped on the midfoot during the next stance phase with the flap deployed, the medial or lateral mid-foot sole would be inverted an average of 10 degrees or everted an average of 9 degrees, depending on the flap deployed. A sample recording from one subject, of the changes in center of pressure (CoP) path during a medial or lateral perturbation relative to that during unperturbed gait is shown in Figure 2, along with the recorded midfoot inversion and eversion angles (Fig. 1B).

The change in CoP trajectory often elicited a response consisting of a change in the length, width or time of the first post-perturbation (recovery) step, compared to the kinematics of

unperturbed gait. The flap was fitted with a ground contact sensor and was retracted at toe-off, not to be deployed again for the remainder of that gait trial. In a pilot study, the perturbing shoes showed good test-retest reliability (average intraclass correlation coefficient for step kinematic variables: 0.834)²⁰.

Experiment

Three tests were administered: gait perturbation, vocal choice reaction, and gait perturbation combined with vocal choice reaction. The gait perturbation tests (with and without vocal choice reaction) each comprised a total of 30 walking trials along a 6-m level walkway. The subjects were told to ambulate at purposeful speed (“as though you were going to mail a letter”) and that a single perturbation would be presented to one foot or the other during trials randomly selected by a computer. In the event, 12 of the 30 trials were perturbed, three each for right foot-medial (RM), right foot-lateral (RL), left foot medial (LM) and left foot-lateral (LL), in randomized order. Baseline step parameters were obtained from at least 20 steps at steady-state gait speed during unperturbed trials. Steady-state gait speed was here defined as in Thies et al.²², being a gait speed of at least 85% of the maximum value during that comfortable gait speed trial. Data collection was preceded by 30 practice trials, with and without perturbation.

An Optotrak Certus motion analysis system (Northern Digital, Inc.) was used to acquire three-dimensional data at 100 Hz from 28 infrared-emitting diode markers placed at bony landmarks in each foot (5), leg (3), thigh (3); the pelvis (3) and mid-sternum (3). Foot switches on the perturbing shoe detected every heel strike. Two force plates along the walkway measured ground reaction force. Foot switch and force plate data were collected at 2 kHz. In addition, surface electrodes were placed on ankle invertors and evertors as well as hip abductors and adductors to record the temporal onset and offset of muscle firing sequences relative to the perturbation. However, those results will not be reported here.

In the vocal choice reaction time test, the participants listened to ten 200 ms-long tones of either high (1,047 Hz) or low (33 Hz) frequency, delivered randomly at 2-second intervals through a headphone fitted with a microphone. Participants were required to respond with a loud “yes” only when they heard a high tone. Additionally, data were obtained from 6 trials of eight additional subjects (4 female) while standing still and during comfortable gait, to examine the effect of gait on vocal choice reaction time.

In the gait perturbation with vocal choice reaction test, there was also a total of 30 walking trials, 12 of which were perturbed using the same setup described above. The tone was phase-locked to sound 174.9 ± 47.8 ms prior to the heel-strike of the stance phase in which the flap was deployed. The vocal response was recorded and synchronized with the optoelectric marker and force plate measurements.

Data processing and statistical analysis

Data were collected at 2 kHz from the foot switches, flap sensor and force plates were low-pass filtered (5th-order Butterworth). A custom MATLAB algorithm (MATLAB® 2011a; The MathWorks, Inc., Natick) was used to post-process all the data and calculate kinematic

parameters (step length, and step width and step time, Fig 1C). Sample kinematic tracings, CoP and EMG responses are shown in Figure 2.

Two primary kinematic outcome variables were studied for each subject: step length and step width. We calculated the effect of the perturbation on step length and step width as the difference (SL and SW respectively) in the mean value of the length and width of the first recovery step following each of the eight medial or lateral perturbations, compared to the mean value of step lengths and widths for at least 20 steps during unperturbed gait at steady-state gait speed²². Recovery step time was calculated as a secondary outcome variable. We also calculated vocal choice reaction times in standing, unperturbed gait and perturbed gait.

The statistical analyses used the data from the 32 subjects to run four one-way, repeated measures, analyses of variance (rm-ANOVA) to estimate the effect of a medial perturbation on a primary recovery step parameter relative to unperturbed gait, a lateral perturbation on a primary recovery step parameter relative to unperturbed gait, a medial perturbation in the presence of a dual task on a primary recovery step parameter relative to unperturbed gait, and a lateral perturbation in the presence of a dual task relative to unperturbed gait. In the 32 subjects, one-way rm-ANOVA was also run to study the effect of the perturbation on vocal reaction time relative to that during standing. Two one-way rm-ANOVA were used in a subgroup of eight subjects to study the effect of unperturbed gait on vocal reaction time relative to that in standing, and perturbed gait relative to unperturbed gait on vocal reaction time. Statistical significance was set at $\alpha = 0.05$.

RESULTS

The differences between step parameters during unperturbed gait (UnP) on one hand, and the first recovery step kinematics after perturbation with (vMP, vLP) or without (MP, LP) auditory distraction on the other, are shown as box- and scatter- plots in Figure 3.

In testing the primary hypothesis relative to the effect of underfoot perturbation in the presence and absence of a dual task on recovery step kinematics, none of the four rm-ANOVAs showed significant effects of the medial or lateral perturbation, with or without the dual task, on the first recovery step width or step length in the 32 subjects (Table 1). For the 32 subjects, a significant effect of the perturbed gait was found on vocal reaction time relative to that measured in standing (one way rm-ANOVA, $p < 0.001$, Fig. 4), with the reaction time being longer during perturbed gait. Similarly, for the eight subjects, the act of unperturbed walking also affected the vocal reaction time compared to standing, lengthening it (one-way rm-ANOVA, $p = 0.002$, Fig. 4), but the trend did not reach significance with respect to the effect of a perturbation on vocal reaction time relative to that in unperturbed gait (one-way rm-ANOVA, $p = 0.104$, Fig. 4).

Vocal response accuracy was excellent in these healthy young adults: out of a total of 1,184 vocal choice reaction trials, subjects were incorrect in only four trials, yielding an error rate of 0.34%. In three trials, no response was given to the high tone and, in one trial, an incorrect response was given.

DISCUSSION

This is the first study to examine the interaction between a vocal reaction time task and execution of the response to a sudden yet familiar, underfoot perturbation of gait. The perturbation had the element of surprise in regard to when (which step) and where (under which foot, and under the medial vs. lateral aspect of that foot) it occurs. The perturbation was felt but never seen. The results suggest that when these healthy young adults walked at their comfortable gait speed, recovery step kinematics after a 9–10 degree magnitude unexpected perturbation to the midfoot was unaffected in the presence or absence of divided attention. Similarly, the underfoot perturbation had no significant effect on the performance of a vocal choice reaction task during gait. These findings suggest that neither task was sufficiently demanding in these healthy young adults under the conditions of the experiment. One might speculate that the perturbation might become more of a challenge at a faster gait speed because of the larger reaction forces acting on the foot.

Yogev-Seligmann and colleagues have reviewed studies which found an interaction between gait and the competing secondary non-gait task²³. For the gait task, most studies have reported on unperturbed gait and measured such parameters as gait velocity, stride length and time, rather than step properties^{15, 16}. Commenting on such studies, Yogev-Seligmann and colleagues remarked that in general, healthy young adults slowed down during gait when performing a concurrent cognitive task²³. Nevertheless, there are investigations that have shown that healthy young adults maintain their stride pattern during dual-tasking^{24,25}. In our study, subjects could not see the perturbation in advance, and auditory distraction had no significant additional effect on the first recovery step response to the sudden underfoot perturbation.

An increase in the width of the first recovery step in response to a postural challenge would clearly be adaptive. Since the plane of instability during gait is the frontal plane, mediolateral adjustments in foot placement are a means of achieving stabilization²⁶. Any reduction in step length is probably driven by the rapid unloading of the perturbed stance limb to minimize the risk of an ankle inversion sprain²⁷. In the box- and scatter- plot of the changes in step length after lateral perturbation with auditory distraction for example (Fig. 3, Table 1), there was a trend toward a shorter step length in response to the lateral perturbation. One can speculate that this trend might become significant if the perturbation had been larger and/or if the subjects walked faster. The main study limitation was the modest subsample of eight subjects used for the test of the effect of the gait perturbation on the vocal reaction time. We did not control for gait speed because we wanted to retain ecological validity by asking each subject to walk “purposefully”. This was not a limitation because when subjects were divided into those walking at 1.39 m/s or above, and those walking at 1.28 m/s or below, no significant effect of speed was found on any of the recovery step kinematic responses.

All the dual task studies on young adults but ours have consistently shown a non-gait task performance deficit. This decrement has been explained on the basis of a shifting of attentional resources away from the non-gait task in order to optimize the response to the gait challenge. This apparent unconscious prioritization of the exigencies of balance control

over the execution of activities unrelated to gait or balance, is in conformity with the “posture-first” strategy identified with healthy young adults²⁸. The absence of a non-gait task performance deficit in our data suggests that the perturbation was both familiar and brief enough so as not to slow the vocal response to an auditory stimulus in these young adults, or the vocal response task itself was not sufficiently demanding .

We conclude that in young healthy adults walking at their comfortable gait speed, an unexpected midfoot angular perturbation of 9–10 degrees in the frontal plane of the foot, in the presence or absence of a vocal reaction time task, is not sufficient to adversely affect step kinematics or vocal response times.

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STUDY HIGHLIGHTS

- We describe a novel protocol for underfoot perturbation during gait using specially-designed footwear.
- We examined the interaction between the execution of the response to a sudden underfoot perturbation of gait and a vocal reaction time task.
- In healthy young adults, recovery step kinematics after perturbation were unaffected by the concurrent performance of a non-gait task.
- In healthy young adults, there was no deficit in the performance of the vocal choice reaction task while responding to this underfoot perturbation.

Figure 1.

Top figure (A) shows an anterior view of the perturbing shoe in three orientations during midstance: left - lateral flap (dotted circle) deployed; middle - no flap deployed; right - medial flap (dotted circle) deployed. Note eversion at left and inversion at right. Middle figure (B) illustrates the change in stance phase ankle inversion angle in a sample unperturbed trial (middle solid line), with medial perturbation (upper dotted line) and with lateral perturbation (lower dashed line). ("0" degree denotes neutral; "+" denotes inversion; and "-" denotes eversion). At bottom (C) is seen an illustration of the first recovery step width and length. The first recovery step time was defined as the time between heel strikes of the perturbed and the first recovery step.

Figure 2.

Sample data from a left foot trial taken from a single subject. At top, the center of pressure (CoP) trajectory is shown for unperturbed stance phase along with that for a medial perturbation. In the second row, the ground reaction force (GRF) vs. time plots are shown for unperturbed (UnP) gait at left and a medial perturbation (MP) at right. In the third row, sample CoP trajectories are shown in the horizontal (HOR) plane. In the bottom row, long peroneal (PER-L) muscle electromyographic (EMG) responses are shown. The arrow denotes the onset of ground contact of the flap, and the bars underline the response to the perturbation.

Figure 3.

Summary box- and scatter-plots of the change in recovery step kinematics (ΔSL , ΔSW , ΔST ; on y-axis) from the unperturbed step values for single task and dual task tests in the 32 subjects. On the y-axis, ΔSL , ΔSW , ΔST are defined in the text as the change in mean recovery step parameter from the mean step parameter during unperturbed gait. Hence a “0” value on the y-axis denotes “no change” in the step parameter. A positive value of ΔSL or ΔSW indicates a longer step length or wider step width.

Figure 4.

Effect of posture and gait (unperturbed and perturbed) on median, upper and lower quartiles, and 95th percentile vocal choice reaction time (vCRT) in healthy young subjects. The indicated p value involves a comparison in 32 subjects. “*” denotes significant effect in eight subjects ($p < 0.005$, rm-ANOVA).

Table 1

Results from eight separate one-way repeated measures ANOVA on single or dual task step kinematics.

	MP		LP	
	F	p-value	F	p-value
Single Task	SW	1.17 0.29	0.03	0.863
	SL	0.58 0.456	2.91	0.102
Dual Task	SW	0.58 0.456	1.04	0.319
	SL	0.05 0.832	3.41	0.078

MP and LP: Medially and laterally perturbed trials respectively. SW and SL: step width and step length respectively. Single task is response to an underfoot perturbation alone. Dual task is the combination of response to an underfoot perturbation and vocal choice reaction.