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Changes in motor actions in the face of varying task constraints

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Abstract

Background: Walking is an everyday activity that requires modifying patterns based on constraints posed by the environment. Meeting multiple constraints at once increases the challenge of modifying motor actions.

Research Question: We asked if adults' strategies in adapting to spatial and temporal constraints were similar and if they would prioritize one constraint over the other when completing both.

Methods: Across three tasks, we investigated how adults altered their walking to cope with crossing obstacles (Task 1; N=30), walking to a metronome beat (Task 2; N=32), and crossing obstacles while walking to a metronome beat (Task 3; N=30).

Results: Adults recalibrated to their baseline gait, but showed carryover effects after meeting a temporal constraint (all $p > .05$). We found an effect on the magnitude of deviation from metronome paces ($F(2,62)=58.86$, $p < .01$). At the slow pace, participants stepped sooner than the beat, and at the fast pace they stepped later than the beat (all $p < .01$). Adults altered the kinematics of their walking in response to a spatial constraint, but changed both the kinematics and kinetics of their walking patterns to meet temporal and combined spatial and temporal constraints. When attempting to meet both a spatial and temporal constraint simultaneously, they stepped sooner than the beat at all metronome paces (all $p < .01$).

Significance: Our findings show separate walking strategies in adapting to spatial and temporal constraints. The presence of more than one constraint leads to prioritizing one over the other (i.e., a spatial constraint over a temporal constraint). These findings highlight that strategies for meeting constraints are dependent upon the type and number of constraints presented.

Keywords

adaptation; gait; walking; constraints; motor

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Skilled motor actions require adapting to change to cope with multiple sources of variability [1]. One source of variability is the environment, which creates constraints. For instance, the ground is not usually flat and uniform. Surfaces are rife with obstacles or slopes. Under such conditions, adults have walked more slowly when approaching high versus low obstacles [2] and taken shorter steps to descend steep slopes [3]. Even healthy individuals reduce their cadence by maintaining their step length when walking on uneven surfaces [4]. Rote motor actions are suited to unchanging environments, but result in poor outcomes under task constraints [5].

Adapting to change becomes even more complex when more than one constraint needs to be met simultaneously. Often, task constraints do not appear in isolation. Difficulty with meeting the goals of more than one task constraint can result in sacrificing one constraint for another. Dual task constraints pose an increased challenge to adapting motor actions, and therefore, increase safety risks [6]. Studies on dual tasking have presented a motor component along with a cognitive task with a focus on imposing cognitive load during an ongoing motor task [7]. We know less about how individuals match their physical capabilities [8] to constraints [9,10] and adapt their actions to meet two motor constraints at once.

Across three different tasks, we examined the ways in which adults modified their walking patterns to cope with task constraints that were spatial (crossing obstacles), temporal (walking to an audio metronome), and both spatial and temporal (crossing obstacles as they walked to an audio metronome). We investigated whether adults' strategies in adapting to spatial and temporal constraints were similar and whether they would prioritize one constraint over the other when faced with doing both.

Methods

Ethics Statement

The study was approved by the Boston University Institutional Review Board and conformed to the Declaration of Helsinki. Informed written and verbal consent were obtained before testing began.

Participants

A total of 92 college-aged students participated for Task 1 ($n=30$), Task 2 ($n=32$), and Task 3 ($n=30$); Tables 1A–C. Participants were recruited from Boston University and tested in the Motor Development Laboratory at Boston University. Inclusion criteria were having a normal BMI ($19\text{--}25\text{ kg/m}^2$), being able to walk independently, having no significant cardiovascular, musculoskeletal, vestibular, or other neurologic disorders. These criteria were confirmed via participant reports and experimenters' observations.

Equipment

Participants completed a series of three tasks that were each 30 minutes long: obstacle crossing (*Task 1*), walking to an audio metronome beat (*Task 2*), and crossing obstacles while walking to an audio metronome beat (*Task 3*). For *Task 1*, participants' gait

parameters were obtained using GAITRite Electronic Walkway (GAITRite Inc., Clifton, New Jersey, USA). The pressure-sensitive gait carpet (5.25 m long $\times$ 0.88 m wide) measured the distance (x and y coordinates) and timing of each footfall at a spatial resolution of 1.27 cm and a sampling frequency of 120 Hz. Obstacles were made of a wooden dowel (81 m long and 2 cm in diameter) inserted into two wooden towers (25 cm high). Obstacle heights were changed by moving the dowel to one of three holes located in the towers. Each hole was positioned at 4 cm, 8 cm, and 16 cm to create low, medium, and high obstacles respectively. For *Task 2*, participants walked on a 6.10 m long $\times$ 0.89 m wide pressure-sensitive gait carpet (Protokinetics, LLC; Peekskill, NY, USA). The walkway uses an x-y coordinate system to acquire spatial and temporal gait parameters at a sampling frequency of 120 Hz with a spatial resolution of 1.27 cm and a temporal resolution accuracy of 1 sample. The Protokinetics mat has an internal metronome with a range starting at 40 beats per minute (BPM) and ending at 208 BPM with an output signal that synchronized the gait data and metronome. For *Task 3*, as in *Task 2*, trials were run on a 6.10 m long $\times$ 0.89 m wide pressure-sensitive gait carpet (Protokinetics, LLC; Peekskill, NY, USA). Obstacles were created using the same equipment described in *Task 1* and metronome beats were played using the same equipment as in *Task 2*.

Task 1.—Participants completed two walking conditions: walking on flat ground and crossing obstacles of different heights for a total of 50 trials. All participants walked barefoot at a self-selected pace. They began trials standing at the edge of the carpet, and ended trials a few steps after walking off of the carpet. Trials began and ended walking with verbal prompts from the experimenter (i.e. “Go” and “Stop”). There were five walking conditions: initial baseline, low, medium, and high obstacles, and final baseline. During the initial and final baselines, participants walked along the path with no obstacles. For the obstacle trials, participants stepped over obstacles in the middle of the path and walked to the end of the walkway ten times. Obstacle heights were counterbalanced but were blocked by height. At the end, they walked on flat ground for ten trials at their own pace.

Task 2.—Participants were instructed to walk to a metronome beat by making their heels contact the ground when the beat played for 56 trials. All participants walked barefoot, began trials standing at the edge of the carpet, and ended trials a few steps after walking off of the carpet. They began with the experimenter’s verbal signal “Go” and ended walking upon hearing “Stop”. Participants performed ten trials in five walking conditions: three at an imposed pace with three different metronome beats (slow, normal, and fast) and two at a self-selected pace without a metronome beat (initial and final baselines). Two intermediate baseline trials without the metronome beat were interspersed between normal, fast, and slow beats, respectively. Sessions began with the initial baseline in which they walked at a self-selected pace without a metronome beat. For each participant, we averaged the cadence from their ten initial baseline trials to calculate the “normal” pace. Then participants walked at three different metronome conditions: normal, slow (25% slower than the normal pace), and fast (25% faster than the normal pace) with two intermediate baseline trials after each pace. The metronome paces were counterbalanced and all of the metronome trials were blocked. Finally, at the last baseline condition, participants walked for ten trials at a self-selected pace.

Task 3.—Participants crossed obstacles to the beat of an audio metronome. There were eleven conditions: the initial baseline, a slow beat with low, medium, and high obstacles, a normal beat with low, medium, and high obstacles, a fast beat with low, medium, and high obstacles, and the final baseline. All participants began with an initial baseline condition walking at a self-selected pace with no metronome or obstacles for ten trials. Participants' normal pace was calculated by averaging their cadence from the ten initial baseline trials. This cadence was then used to create individualized slow and fast metronome paces for each participant. Slow and fast paces were 15% lower and higher than the normal metronome pace. Next, participants crossed three different obstacle heights: low (4 cm), medium (8 cm), and high (16 cm) at normal (average pace calculated from their first ten trials), slow (15% slower than their normal pace), and fast (15% faster than their normal pace) paces. All participants completed each for five trials. At the end, participants walked on flat ground for ten trials at their own pace. All participants were assigned to one of six randomized orders for metronome paces: slow-normal-fast, slow-fast-normal, normal-slow-fast, normal-fast-slow, fast-slow-normal, and fast-normal-slow. Obstacle heights were counterbalanced. All trials were blocked by both metronome pace and obstacle height.

Data Processing

Task 1.—The dependent variables were maximal center of pressure (COP) velocity (how quickly maximum areas of pressure exerted beneath each foot moved during walking) during the double limb support phase, cadence (steps per minute), step length (distance between consecutive steps), step width (lateral distance between feet), and double limb support time (time spent balancing on both feet). COP velocity was calculated for each leg. For all conditions, average values for all trials were recorded for each of the parameters. A custom software written in MATLAB (R2015a, Mathworks, Natick, MA, USA) was used to process the COP data.

Task 2.—Dependent variables were the same as in *Task 1*. Data were obtained from the raw pressure data extracted from the ProtoKinetics Movement Analysis Software (PKMAS) version 5.07C7. A custom software written in MATLAB (Mathworks, R2015a, Natick, MA, USA) was used to process the data.

Task 3.—Our dependent variables were the same as in *Tasks 1 and 2*. Data processing was the same as in *Task 2*.

Statistical Analyses

Statistical analysis was performed using SPSS (Version 20.0 for Windows, SPSS Inc., Chicago, IL, USA). The mean and standard deviation scores of the dependent variables were computed for each trial and condition. The ratio of standard deviation to mean, the Coefficient of Variation (CV), was used as a measure of variability. The CVs were multiplied by 100 to be represented as percentages. During the initial and final baselines, relationships between the dependent variables were characterized with Pearson's correlations and were compared with paired t-tests. Significance was set at $\alpha < 0.05$. Post hoc analyses consisted of pairwise comparisons and were subjected to Bonferroni corrections.

Task 1.—One-way repeated measure (RM) ANOVAs with one independent variable, obstacle height (low, medium, and high), were conducted to examine differences in the dependent variables.

Task 2.—One-way RM ANOVAs with one independent variable (slow, normal, and fast metronome beat), were carried out on each dependent variable. RM ANOVAs were also conducted on three additional variables: the ability to meet the metronome paces, magnitude of deviation from the metronome paces, and carryover effects. We measured the ability to meet the metronome pace with a measure called the metronome index: the difference between participants' heel contact and the time at which the metronome beat played. Metronome index scores could be zero (perfectly meeting the beat), positive (walking faster than the beat) or negative (walking more slowly than the beat). How much participants deviated from the metronome beat was measured by taking the absolute value of the metronome index score: magnitude of deviation. Carryover effects were examined by comparing dependent variables during the two intermediate baseline trials to the initial baseline trials.

Task 3.—Separate three-way RM analysis of variance (ANOVA)s (3 metronome $\times$ 3 obstacle $\times$ 2 trailing or leading steps) were run on the dependent variables. The Pearson correlation coefficient was used to examine correlation between obstacle crossing performance.

Results

Task 1: Obstacle crossing

Between the initial and final baselines, there were no differences in any of the dependent variables (Table 2A). There was a main effect for obstacle on cadence ($F(2,58)=42.47$, $p<.01$). Participants' cadences were greater at the low compared to the medium and high obstacles (Table 2B). There were main effects of obstacle height on both step length ($F(2,58)=23.01$, $p<.01$) and step width ($F(2,58)=4.28$, $p<.05$). Participants increased their step length ($p<.01$) and step width ($p<.05$) as the obstacle height increased (Table 2B). There was no main effect of obstacle height on double limb support time ($p>.05$) and no effects of obstacle on the maximal velocities of the COP ($ps>.05$, respectively).

Task 2: Walking to an audio metronome

Between the initial and final baselines, there were no differences in the dependent variables (Table 3A). However, participants demonstrated carryover effects at the intermediate baseline conditions. At the first trial for the intermediate baseline, participants walked more slowly after the slow pace and faster after the fast pace. As the metronome pace increased, COP velocity decreased for the stance leg and increased for the swing leg.

There was a main effect for metronome beats on cadence ($F(2,62)=1704.48$, $p<.01$). Participants' cadence was greater at the fast than at the normal and slow metronome paces (Table 3B). There was a main effect for double-limb support time ($F(2,62)=54.14$, $p<.01$). Double limb support time decreased as the metronome pace increased. There were main

effects for step length and step width ($F(2,62)=34.48$, $p<.01$, $F(2,62)=32.817$, $p<.01$, respectively). Participants increased their step length and step width as the metronome pace increased (all $ps<.01$).

We found an effect on the magnitude of deviation from the pace ($F(2,62)=58.86$, $p<.01$). As the metronome pace changed, participants deviated more from the pace (Figure 1). At the slow pace, participants stepped sooner than the beat, and at the fast pace they stepped later than the beat (all $ps<.01$).

For both feet, there were significant effects on the maximal velocities of the COP during double limb support ($F(2,62)=96.66$, $p<.01$, $F(2,62)=39.01$, $p<.01$, respectively). Participants demonstrated increased COP velocity for the swing leg but decreased COP velocity for the stance leg as the metronome pace increased. They also showed increased variability via CV of the COP velocity with the swing leg ($F(2,62)=10.78$, $p<.01$), while no variability existed in the stance leg (Figure 6 C-2, $F(2,62)=0.73$, $p=.49$). At the slow and fast pace, compared to the normal pace, participants showed more variability of COP velocity with the swing leg (all $ps<.01$).

Task 3: Crossing obstacles while walking to an audio metronome

Between the initial and final baselines, there were no differences in cadence, step length, step width, double limb support time (Table 4A), COP velocity, and its CVs (all $ps>.05$).

There were main effects of both auditory metronome and obstacle on cadence (Tables 4B–C). Participants' cadences were higher at the fast versus the slow metronome pace. Cadence was lower at the high versus the low obstacle height. There was a main effect of the metronome on step length; step length increased as the metronome pace increased (all $ps<.01$). There were no main effects of obstacle on both step length and step width (all $ps>.05$). Participants decreased double limb support time as the metronome pace and the obstacle height increased (all $ps<.01$).

We found significant effects for how much participants' steps deviated from the metronome while crossing obstacles to the beat; they stepped sooner than the beat at all metronome paces (all $ps<.01$). There was also a main effect for trailing/leading steps on the magnitude of deviation from the metronome pace during obstacle crossing; as the metronome pace increased, steps taken with the leading leg deviated less from the metronome than the trailing leg (all $ps<.01$).

For the leading leg, there were main effects of both metronome and obstacle on the maximal velocities of the COP during initial double limb support (Figure 2, all $ps<.05$). Participants increased their COP velocity for the leading (swing) leg as the obstacle height and metronome pace increased (all $ps<.01$). However, the COP velocity for the trailing (stance) leg remained the same (all $ps>.05$). There were main effects of the metronome on the CVs of COP velocity for only trailing leg. As the metronome pace increased, participants showed more variability of COP velocity (Figure 2, all $ps<.05$). However, there were main effects of the obstacle on the CVs of COP velocity for both trailing and leading leg (Figure 2, all $ps<.05$).

05). As the metronome pace and obstacle height increased, participants showed more variability of COP velocity during double limb support.

Discussion

We aimed to examine how adults adapted their walking to meet task constraints that were spatial (Task 1), temporal (Task 2), and both spatial and temporal (Task 3). Participants recalibrated to their baseline walking patterns by the end of each task, but demonstrated carryover effects after walking to the metronome paces.

Across all three tasks, adults recalibrated to their normal walking by the end of the session; there were no differences in gait from the initial to final baseline. Other studies have found similar results. For example, when the length of one leg is artificially extended with a platform attached to a shoe, adults increase step length with the longer leg but return to taking equivalent step lengths once the platform is removed [11]. Adults have many years of experience to hone in on a typical walking pattern. Therefore, shifts away from the pattern of walking are often temporary unless an injury is present [12]. Also, returning to original walking patterns is advantageous because it avoids permanently changing the existing pattern of walking for a constantly changing environment.

The participants in our tasks altered the kinematics of their walking when trying to meet task constraints. In other studies, adults have attempted to increase postural stability by increasing step width in the face of physical [13] and environmental [14] constraints. We tested healthy participants who had the wherewithal to pare down the modifications in their walking kinematics to changes that might maximize meeting a constraint (increasing step length) instead of changes that maximize postural stability (increasing step width). Maintaining postural stability can be secondary for adults who have the ability to recover from a loss of balance [15].

Tasks that pose more than one constraint at a time increase the difficulty of achieving goals causing adults to sacrifice one constraint for another [16, 17]. For instance, when avoiding obstacles during a cognitive task, adults show increased rates of failure during crossing [18, 19]. Our results match this assumption. Specifically, during Task 3 when asked to meet both the metronome and obstacle constraints, participants prioritized obstacle crossing over the metronome task. One limitation of this study is that we tested different participants across the three tasks rather than asking the same participants to complete all three tasks. In future studies, we hope to use a longitudinal design to examine within subject differences in adapting to varying external constraints. Obstacle crossing may have elicited a greater demand to maintain postural control than keeping pace with the metronome [17]. Also, participants may have prioritized what they perceived to be the easier of the two tasks. Our obstacle heights were fixed [14]. However, our metronome paces were individualized [20,21]. The difficulty of meeting the metronome pace could have been more challenging than crossing fixed obstacle heights.

Conclusions

The challenge of adaptation increases when multiple constraints are present. The nature of the constraint posed yields different adaptive patterns such as changes in the kinematics or kinetics of walking. Our findings show separate walking strategies in adapting to spatial and temporal constraints. The presence of more than one constraint leads to prioritizing one over the other (i.e., a spatial constraint over a temporal constraint).

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Highlights

- We asked if adults would prioritize a constraint during two constraints
- Adults crossed obstacles, walked to a metronome, and both
- Adults recalibrated to their baseline gait by the end of each task
- Adults prioritized the obstacle over the metronome task when face with both
- Strategies for meeting constraints depend on the type and number of constraints

Figure 1. Maximal center of pressure (COP) velocity during baseline (A-1), intermediate baseline (B-1), and metronome (C-1) conditions for the stance and swing legs; Coefficient of variation (CV) of the maximal COP velocity during baseline (A-2), intermediate baseline (B-2), and metronome (C-2) conditions.

Figure 2.

Maximal COP velocity during baseline (A-1), metronome baseline (B-1), and obstacle (C-1) conditions for the stance (trailing) and swing (leading) legs; CVs of the maximal COP velocity during baseline (A-2), metronome baseline (B-2), and obstacle (C-2) conditions.

Table 1A.

Demographics and anthropometric information for Task 1: Crossing an obstacle. Means are listed with standard deviations in parentheses.

Characteristics	Crossing an obstacle (N=30)
Age (yr)	22.59 (3.01)
Height (m)	165.62 (8.06)
Body Mass (kg)	63.52 (12.48)
BMI (kg/m^2)	23.10 (3.98)

Table 1B.

Demographics and anthropometric information for Task 2: Walking to a beat. Means are listed with standard deviations in parentheses.

Characteristics	Walking to a beat (N=32)
Age (yr)	22.97 (3.82)
Height (m)	169.94 (9.55)
Body Mass (kg)	66.07 (13.11)
BMI (kg/m ²)	22.67 (2.72)

Table 1C.

Demographics and anthropometric information for Task 3: Crossing obstacle to a beat. Means are listed with standard deviations in parentheses.

Characteristics	Crossing an obstacle to a beat (N=30)
Age (yr)	23.07 (2.99)
Height (m)	169.62 (10.50)
Body Mass (kg)	68.77 (12.61)
BMI (kg/m^2)	23.8 (3.1)

Table 2A.

Means and standard errors from baseline condition (Task 1: Crossing an obstacle)

	Initial Baseline	Final Baseline
Cadence (steps/min)	117.485 (1.494)	117.847 (1.713)
Step length (cm)	34.670 (0.768)	35.777 (0.582)
Step width (cm)	7.418 (0.391)	6.960 (0.362)
Double support time (msec)	105.87 (3.02)	100.64 (3.00)

*
= $p < .05$,

**
= $p < .01$: Two different baseline condition

Table 2B.

Means and standard errors from obstacle condition (Task 1: Crossing an obstacle)

	Low	Medium	High
Cadence (steps/min)	109.13 (1.54) **	103.99 (1.94) **	99.01 (1.93) **
Step length (cm)	43.32 (1.07) **	45.83 (0.86) **	48.10 (0.79) **
Step width (cm)	7.71 (0.43)	8.27 (0.42) *	8.46 (0.45) *
Double support time (msec)	93.29 (3.01)	97.30 (3.01)	110.35 (3.07) **

*
= $p < .05$,**
= $p < .01$: Three different obstacle condition

Table 3A.

Means and standard errors from baseline condition (Task 2: Walking to a beat)

	Initial Baseline	Baseline after Slow	Baseline after Normal	Baseline after Fast	Final Baseline
Cadence (steps/min)	112.43 (1.98)	110.42 (2.08) **	112.72 (2.02)	118.52 (2.06) **	112.43 (2.09)
Step length (cm)	64.04 (0.74)	64.37 (0.78)	64.33 (0.77)	65.71 (0.88)	63.94 (0.78)
Step width (cm)	11.12 (1.30)	11.17 (1.36)	11.18 (1.31)	11.47 (1.54)	11.12 (1.34)
DS time (msec)	129.20 (4.01)	130.21 (3.10)	128.84 (4.02)	119.00 (5.31) **	129.01 (3.00)

*
= $p < .05$,**
= $p < .01$: Three different obstacle condition

Table 3B.

Means and standard errors from metronome condition (Task 2: Walking to a beat)

	Slow	Normal	Fast
Cadence (steps/min)	85.26 (1.65) **	112.21 (2.03) **	136.12 (2.41) **
Step length (cm)	59.25 (0.97) **	63.99 (0.65) **	66.72 (0.98) **
Step width (cm)	10.29 (1.7) **	11.11 (1.13) **	11.64 (1.79) **
DS time (msec)	184.03 (5.11) **	127.03 (5.11) **	96.59 (5.02) **

*
= $p < .05$,**
= $p < .01$: Three different obstacle condition

Table 4A.

Means and standard errors from baseline condition (Task 3: Crossing obstacle to a beat)

	Initial Baseline	Final Baseline
Cadence (steps/min)	113.65 (3.21)	112.55 (1.98)
Step length (cm)	64.51 (1.23)	65.01 (0.99)
Step width (cm)	11.22 (0.22)	11.33 (0.17)
Double support time (msec)	136.81 (4.24)	133.22 (5.01)

*
= $p < .05$,

**
= $p < .01$: Two different baseline condition

Table 4B.

Means and standard errors from metronome condition (Task 3: Crossing obstacle to a beat)

	Slow Metronome	Normal Metronome	Fast Metronome
Cadence (steps/min)	95.52 (1.76) **	110.43 (1.93) **	123.29 (1.99) **
Step length (cm)	62.29 (0.93) **	64.70 (0.93) **	65.54 (1.01) **
Step width (cm)	10.36 (0.52)	10.43 (0.59)	10.27 (0.52)
Double support time (msec)	136.23 (5.03) **	109.10 (4.33) **	91.58 (3.14) **

*
= $p < .05$,**
= $p < .01$: Three different obstacle condition

Table 4C.

Means and standard errors from obstacle condition (Task 3: Crossing obstacle to a beat)

	Low	Medium	High
Cadence (steps/min)	110.60 (1.83) *	110.02 (1.79)	108.61 (1.91) *
Step length (cm)	64.53 (0.94)	64.39 (0.89)	63.614 (0.86)
Step width (cm)	10.22 (0.52)	10.29 (0.55)	10.55 (0.52)
Double support time (msec)	118.75 (4.10) **	111.22 (4.32) **	108.01 (4.43) **

*
= $p < .05$,**
= $p < .01$: Three different obstacle condition