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Effects of temporal constraints on medio-lateral stability when negotiating obstacles

Wataru Nakano [a,*], Takashi Fukaya [a], Yoshihide Kanai [b], Kazunori Akizuki [c], Yukari Ohashi [b]

[a] Department of Physical Therapy, Tsukuba International University, 6-8-33 Manabe, Tsuchiura, Ibaraki, Japan
[b] Department of Physical Therapy, Ibaraki Prefectural University of Health Sciences, 4669-2 Ami, Ami, Ibaraki, Japan
[c] Department of Physical Therapy, Mejiro University, 320 Ukiya, Iwatsuki, Saitama, Japan

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ABSTRACT

If an obstacle suddenly appears during walking, either the crossing step can be lengthened or the precrossing step shortened to avoid the obstacle. We investigated the effects of temporal constraints on dynamic stability during step adjustments. Twelve healthy young adults avoided a virtual white planar obstacle by lengthening or shortening their steps under free or constrained conditions. When constrained, participants had only one step to avoid the obstacle. The results indicated that center of mass (COM) displacement in the mediolateral (ML) direction and the COM velocity toward the swing-leg side during the crossing step were significantly increased in the long-constraint compared with the long-free condition. Consequently, the extrapolated COM (XcoM) position at the swing foot contact was also located further toward the swing-leg side. However, the distances between the XcoM and base of support (BOS) at the swing foot contact in the ML direction was unchanged because of greater lateral foot placement. In the anteriorposterior (AP) direction, temporal constraints led to greater AP COM displacement. The XcoM–BOS distance in the AP direction was unchanged in the long-constraint condition because of greater step length. However, the value became negative in the short-constraint condition, violating the conditions for dynamic stability, because step length adjustments were obstructed by the spatial constraints of the obstacles. These results suggest that temporal constraints affect postural stability in the AP and ML directions during step adjustments. AP and ML stability at swing foot contact are maintained through adjustments of step length and lateral foot placement, respectively.

1. Introduction

Falls among older individuals often occur during walking, and tripping and slipping are major contributors [1,2]. A previous systematic review reported that older adults are at greater risk of contacting obstacles under time-constrained conditions [3]. Most falls in older adults occur laterally because of deficits in lateral stability control [4,5]. Therefore, it is important to understand dynamic stability control in the mediolateral (ML) direction during obstacle avoidance under temporal constraints.

If an obstacle suddenly appears during walking, a long step strategy (LSS) or a short step strategy (SSS) can be used [6]. In an LSS, the obstacle is crossed using a lengthened crossing step. In an SSS, the precrossing step is shortened and the obstacle is crossed on the next step. Previous research has shown that sudden lengthening of the crossing step results in a loss of balance in the lateral direction [7]. Another study reported that sudden shortening of the precrossing step leads to falling without contacting an obstacle [6]. These results suggest that step adjustments under temporal constraints cause instability.

To our knowledge, only one study has quantified dynamic stability during step adjustments under temporal constraints [8]. This study reported that stability in the anteroposterior (AP) direction deteriorated in an SSS, whereas ML stability was not affected by either an LSS or an SSS. In contrast, recent studies have shown that ML stability control is influenced by temporal constraints during volitional stepping and gait initiation [9–12]. These discrepancies might be explained by the modulation of

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* Corresponding author at: Department of Physical Therapy, Tsukuba International University, 6-8-33 Manabe, Tsuchiura, Ibaraki 300-0051, Japan. Tel.: +81 29 826 6622; fax: +81 29 826 6776.

E-mail addresses: w-nakano@tius.ac.jp (W. Nakano), t-fukaya@tius.ac.jp (T. Fukaya), kanai@ipu.ac.jp (Y. Kanai), akiduki@mejiro.ac.jp (K. Akizuki), ohashi@ipu.ac.jp (Y. Ohashi).

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lateral foot placement. Caderby et al. [12] reported that temporal constraints led to greater center of mass (COM) shift toward the swing-leg side during gait initiation, whereas the margin of dynamic stability (MDS; the distance between the base of support and the extrapolated COM) at the swing foot contact in the ML direction was maintained because of regulation of lateral foot placement. Thus, the effects of temporal constraints on dynamic stability control during step adjustments should be evaluated by not only MDS but also COM motion and foot placement.

The purpose of this study is to clarify the effects of temporal constraints on dynamic stability control during step adjustments. We presumed that AP stability control is affected by the SSS, whereas ML stability control is affected by the LSS. Our hypotheses were: (1) sudden lengthening of the crossing step leads to greater ML COM motion; (2) MDS in the ML direction is maintained by adjustments of lateral foot placement; and (3) MDS in the AP direction is affected by sudden shortening of the precrossing step.

2. Method

2.1. Participants

Twelve healthy young adults volunteered for this study (six female; mean age 25.6 ± 4.6 years; mean height 162.0 ± 7.2 cm; mean weight 56.2 ± 8.4 kg). All participants completed informed consent procedures approved by the local ethics committee.

2.2. Apparatus

The present protocol replicated the protocol of Moraes et al. [8]. A liquid crystal display monitor (41.8 cm × 55.6 cm; IIYAMA, ProLiteE-2473HDS-B, Tokyo, Japan) was embedded in a walkway (5.4 m × 0.9 m). A piece of tempered glass was placed over the monitor so that participants could step over it normally. A virtual white planar obstacle measuring 10 cm (depth) × 39 cm (length) was projected onto the middle of the monitor. The size of the obstacle was identical for all participants. A mat switch (operating force > 60 N; OJIDEN, OM-PVC623, Osaka, Japan) was connected to the monitor through the computer, and the obstacle was projected onto the monitor when participants stepped on the switch. Kinematic data were measured using an 8-camera motion analysis system (Oxford Metrics Group, Vicon Nexus, Oxford, UK) with a 100-Hz sampling rate.

2.3. Procedure

Twenty-two reflective markers were attached to the participants' bodies, positioned at: vertex, upper margin of sternum, left/right middle of tragus, acromion, elbow joint, wrist joint, third metacarpophalangeal joint, greater trochanter, knee joint, lateral malleolus, and calcaneal tuberosity. Two reflective markers were also attached to the monitor to define the obstacle position. All participants stood in a natural upright posture at the starting position, and started walking with their left foot at a self-paced speed. The starting position was adjusted so that the middle of the right foot on the fourth step was located in the center of the obstacle (Fig. 1). The switch was located at the position of the third left heel contact. Tape showing the normal landing spot of the third left heel contact was placed on the switch. Participants were asked to walk several times to confirm whether the third left heel contact was on the switch and that the right foot on the fourth step was at the center of the obstacle without step adjustments. Gaze direction during the initial posture and the walk was not controlled.

For obstacle conditions, participants avoided the obstacle by either lengthening or shortening their steps. The adjustment strategy to be performed was indicated using a arrow on the monitor (Fig. 1). Participants performed obstacle avoidance tasks under two temporal conditions: free or constrained. For the free condition, the obstacle and arrow were projected when participants stood at the starting position. For the constrained condition, the obstacle and arrow were projected when they stepped on the switch. Four obstacle conditions were collected in total: long-free (LF), long-constrained (LC), short-free (SF) and short-constrained (SC). Each participant performed five trials per condition. Participants could anticipate the obstacle appearance if the obstacle was invisible from the starting position (constrained conditions). To minimize anticipation, 10 walk-through trials were collected. The probability of obstacle appearance was 50% if the obstacle was invisible from the starting position. Also, participants were asked to step on the tape on the switch for both walk-through and constrained conditions.

Participants initially performed three normal-walking trials with the obstacle and arrow not shown. Participants knew that the obstacle would not appear, and adjusted their step length without constraints to step on the switch or tape. Then, they performed at least two familiarization trials for each obstacle condition and walk-through condition followed by 20 obstacle trials and 10 walk-through trials. Trials were completely randomized. The main difference between the normal-walking and walk-through

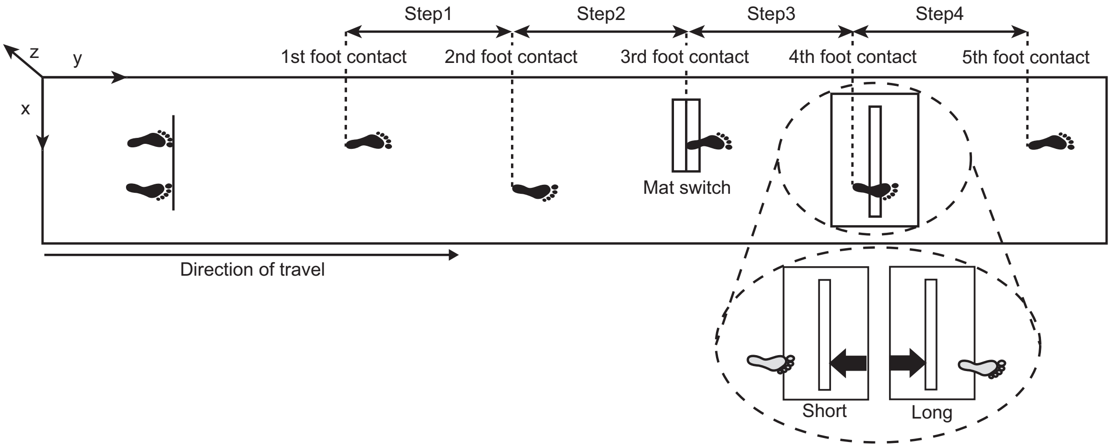

Fig. 1. Schematic of the experimental set-up. Experimental set-up showing virtual white planar obstacle (10 cm × 39 cm) and a arrow projected on the monitor. The arrow indicated the adjustment strategy (long or short) to be performed. The obstacle and the arrow were visible from the starting position for the free condition, and in the constrained condition they appeared when participants stepped on the mat switch.