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GENERALIZATION OF MOTOR ADAPTATION TO REPEATED-SLIP PERTURBATION ACROSS TASKS

T.-Y. WANG,[a,b] T. BHATT,[a] F. YANG[a] AND Y.-C. PAI[a,b]*

[a]*Department of Physical Therapy, University of Illinois at Chicago, Chicago, IL 60612, USA*

[b]*Department of Kinesiology and Nutrition, University of Illinois at Chicago, Chicago, IL 60612, USA*

Abstract—Similar adaptations improve both proactive and reactive control of center-of-mass (COM) stability and limb support against gravity during different daily tasks (e.g., sit-to-stand and walking) as a consequence of perturbation training for resisting falls. Yet it is unclear whether—or to what extent—such similarities actually promote inter-task generalization. The purpose of this study was therefore to determine whether young adults could indeed transfer their adaptive control, acquired from sit-to-stand-slip, to improve their likelihood of a recovery from an unannounced novel slip in walking. Subjects underwent either repeated slips during sit-to-stand before experiencing an unannounced, novel slip during walking (training group, $n=20$), or they received no prior training before the same gait-slip (control group, $n=23$). The subjects demonstrated training-induced generalization of their improved proactive control of stability in post-training (unperturbed) gait pattern that was more stable against backward balance loss than was that of their own pre-training pattern as well the gait pattern of the subjects in the control group. Upon the unannounced novel gait-slip, the training group showed significantly lower incidence of both falls and balance loss than that shown by the control, resulting from the improvements in the reactive control of limb support and slip velocity, which directly influenced the control of their COM stability. Such transfer could occur when the subjects' central nervous system recalibrates the non-task-specific, generalized representation of stability limits during the initial training to guide both their feed-forward adjustments and their feedback responses. The findings of the inter-task generalization suggests that behavioral changes induced via the perturbation training paradigm have the potential to prevent falls across the spectrum of cyclic and non-cyclic activities.

Key words: perturbation training, sit-to-stand, gait, stability, limb support, fall.

A vital functional plasticity of the CNS is its ability to take motor adaptations obtained from one situation and apply it appropriately to different "contexts." Such context can mean different effectors (e.g., interlimb generalization) (Bhatt and Pai, 2008a; Morton et al., 2001; Sainburg and Wang, 2002), different environmental constraints (e.g., moveable-platform-to-slippery-floor generalization) (Bhatt and Pai, 2009), or different task objectives (i.e., inter-task generalization) (Abeele and Bock, 2003; Conditt et al., 1997; Lam and Dietz, 2004; Morton and Bastian, 2004; Seidler, 2004). The latter, namely the inter-task generalization, conventionally defined by the improvement of performance in one task resulting from adaptive skills acquired from training in a different task (Schmidt and Lee, 2005), is especially important to clinical interventions that can focus only on a limited small subset of daily activities.

Previous findings have illustrated the CNS's ability to generalize its learned experience and response to similar perturbations occurring in untrained tasks (Lam and Dietz, 2004; Morton and Bastian, 2004; Seidler, 2004). As a prerequisite to generalization, motor adaptation requires a recalibration of motor control to meet novel and changing sensory demands (Bastian, 2008). During this process, the CNS builds and updates its corresponding representation (i.e., a neural representation of the relation between motor commands and movements) where the altered task variables are transformed into intrinsic (e.g., individual joint angle) or extrinsic (e.g., endpoint motion) variables, to more accurately predict the actual outcome using feed-forward mechanisms (Imamizu et al., 1998; Wolpert and Ghahramani, 2000). Few studies have suggested that the CNS is able to code and generalize motor adaptation to changing task objectives by utilizing such an internal representation resulting from motor practice (Conditt et al., 1997; Shadmehr and Mussa-Ivaldi, 1994). When an acquired internal representation is more generalized and not specific to certain effectors, environments, or tasks, a greater degree of motor transfer is likely to be measurable (Morton et al., 2001).

In the context of posture and locomotor control, successful proactive adaptation (i.e., action before onset of perturbation) would include a combination of change within the feed-forward mechanism and its influence on feedback loops. Adaptation can also occur reactively (after onset of perturbation) within "feedback-error based" mechanisms (Atkeson, 1989), as is apparent from the attenuation of both muscle activation and degree of postural sway with repeated support-surface translations (Horak et al., 1989; Nashner, 1976). An appropriate feed-forward mechanism can produce movements that accurately match the predicted sensory consequences and involve little need for real-time feedback adjustment in error correction.

Similarly, both young and older adults were able to adapt to prevent falls and balance loss after repeated exposure to slips induced during sit-to-stand and in walking (Bhatt et al., 2006a; Pai et al., 2010; Pavol and Pai,

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*Correspondence to: Y.-C. Pai, Department of Physical Therapy (MC 898), University of Illinois at Chicago, 1919 W. Taylor Street, Fourth Floor, Chicago, IL 60612, USA. Tel: +1-312-9961507; fax: +1-312-9964583.
E-mail address: cpai@uic.edu (Y.-C. Pai).

Abbreviations: BOS, base-of-support; COM, center-of-mass; FSR, feasible stability region.

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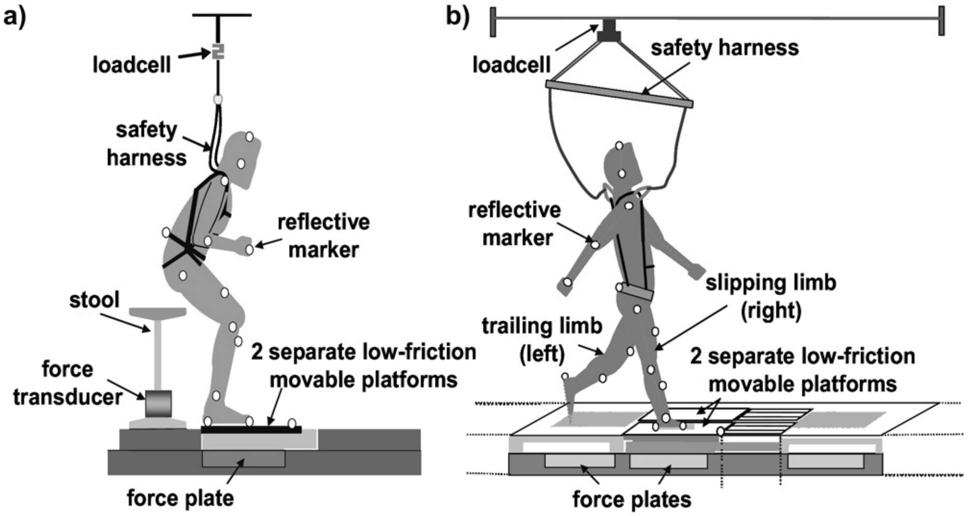

Fig. 1. The diagrammatic representation of the experimental setup for (a) sit-to-stand-slip and (b) gait-slip. (a) The diagram shows the average body position at seat-off. The force exerted on the stool was recorded by the force transducer bolted beneath the stool. (b) The diagram shows average body position at leading/slipping foot touchdown (i.e., right foot). A slip was induced by releasing two low-friction movable platforms shortly after seat-off for sit-to-stand-slip and at the instant of leading/slipping foot touchdown for gait-slip. Each of the two platforms was mounted on a frame with two rows of linear bearings, and the frame was bolted on to two force plates to measure the ground reaction force. During both sit-to-stand-slip and gait-slip, the movable platforms were free to slide 150 cm and 90 cm forward for the right and left, respectively. The movable platforms were embedded in a 7-m walkway and made less noticeable to the subject by surrounding stationary decoy platforms. A set of 28 light-reflective markers were placed on bilateral upper and lower extremities, torso, and platforms. The subjects were required to wear a safety harness which was individually adjusted to prevent a fall to the ground. A load cell was used to measure the force exerted on the harness. Note that the safety harness system was much higher than that shown.

2002; Pavol et al., 2004a). For both tasks, such adaptive control was achieved by improving proactive and reactive control of horizontal stability and vertical limb support against gravity (through both feed-forward and feedback mechanisms) (Pai et al., 2010). It is unclear, however, whether such similarities actually promote inter-task generalization.

The purpose of this study was therefore to determine whether young adults could transfer their adaptive control acquired from a single-session of repeated-slip exposure during sit-to-stand to increase the likelihood of recovery from a novel slip in walking. We hypothesized that these subjects were able to generalize motor adaptation to yield better proactive and reactive control of gait stability and limb support (resulting in their reduced incidence of falls and balance loss in novel gait-slip) than we found in the control group, who received no such training.

EXPERIMENTAL PROCEDURES

Subjects

Forty-three young adults (26 women; 17 men; age 26±5 years; height 168±9 cm; mass 64±11 kg) participated in either the training or control group (training: $n=20$; control: $n=23$). Although 46 subjects were recruited initially, only those 43 subjects who completed the protocol and had a full data set were included for analyses. The remaining three subjects were excluded because of incomplete training or missing data (see *Perturbation training during sit-to-stand*). All subjects gave informed consent and were given full and careful explanation of the purposes and procedures in the study. The study was approved by the Institutional Review Board. None of the subjects had histories of neurological, musculoskeletal, or other systemic disorders that would have affected their postural control. All were right-leg dominant (as determined by self-report of a preference to kick a ball with the right leg).

Experimental setup

The experimental setup was similar to that of our previous studies (Bhatt et al., 2005; Pavol et al., 2002) (Fig. 1). The stool with adjustable seat level (50~62 cm) was bolted to a transducer (MC3A-6-250, AMTI, Newton, MA, USA) and was supported by a specially-built platform. A slip was induced by a side-by-side pair of low-friction movable platforms ($65\times30\times0.6$ cm^3, coefficient of friction <0.05), each of which was mounted on a frame with two rows of linear bearings. The frame was bolted onto two force plates (OR6-7-1000, AMTI, Newton, MA, USA) to measure the ground reaction force. The platforms were free to slide 150 cm and 90 cm forward for the right and left, respectively, when unlocked by a computer-controlled release mechanism. During sit-to-stand, the slip was induced shortly after seat-off by simultaneously unlocking both platforms when the stool supported less than 10% body weight and the forward velocity of the person's body center-of-mass (COM) exceeded 20 cm/s, to standardize the training conditions. Platform release data were computed in real-time from force plates and the transducer beneath the stool, using a computer program written in LabView (National Instruments Inc., Austin, TX, USA). During walking, the slip was induced by computer-controlled unlocking of the moveable platforms at touchdown of the slipping foot. The subjects wore a full-body safety harness and their own athletic shoes. The length of the rope that connected the harness to the overhead low-friction trolley was adjusted so the body parts above the ankles could not touch the ground. A load cell measured the force exerted on the harness.