BALANCE TRAINING VIA MULTIMODAL BIOFEEDBACK

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We have previously demonstrated that vibrotactile feedback of trunk motion significantly improves balance stability in individuals with vestibular deficits and older adults. Recently we have developed a Mobile Instrument for Motion Instruction and Correction (MIMIC) that enables an expert (i.e. physical therapist) to map his/her movements to a trainee (i.e. patient) in a hands-free fashion. MIMIC comprises an Expert Module (EM) and a Trainee Module (TM). Both the EM and TM are composed of six degree-of-freedom inertial measurement units (IMUs), microcontrollers, and batteries. The TM also has an array of vibrating actuators that provides the user with vibrotactile instructional cues. The expert dons the EM, and his/her relevant body position is computed by an algorithm based on an extended Kalman filter that provides asymptotic state estimation. The captured expert body motion information is transmitted wirelessly to the trainee, and based on the computed difference between the expert and trainee motion, directional instructions are displayed via vibrotactile stimulation to the skin. The trainee is instructed to move in the direction of the vibration sensation until the vibration is eliminated. In a proof-of-concept study, five healthy young subjects were instructed to replicate recorded expert anterior-posterior trunk tilt motion using the aforementioned device with vibrotactile, visual, or combined vibrotactile and visual instructional cues. Preliminary results showed that expert-subject cross-correlation values were maximized and time delays and average position errors were minimized when a 0.5 degree position error threshold and proportional plus half derivative control signal of the angle difference between the expert and subject were used. Subjects had significantly reduced position error when replicating the expert motion with combined vibrotactile and visual instructional cues compared to visual instructional cues alone, and slightly reduced error compared to vibrotactile cues alone

Introduction

Physical rehabilitation has been shown to improve sensory integration, motor coordination, and strength in patient populations with balance or vestibular disorders, stroke, or traumatic brain injuries (Crooks *et al.*, 2007; Horak *et al.*, 1992; Mulrow *et al.*, 1994; Ones *et al.*, 2009). During conventional rehabilitation and training, physical therapists communicate proper execution of an exercise to patients through a combination of instruction (verbal, demonstration), feedback (auditory, visual, haptic), and/or physical guidance. Verbal instruction and demonstration are provided prior to and/or during the execution of the rehabilitation exercise and are typically used in combination with augmented extrinsic feedback or knowledge of results (KR). The impact of KR on motor learning varies as a function of the frequency, delay, and precision with which information is provided (Winstein, 1991).

Vibrotactile sensory substitution technologies have been used to display direction and magnitude of trunk tilt information via stimulation of the skin in order to increase postural stability during quiet and perturbed stance in both individuals with vestibular deficits and older adults (Sienko *et al.*, 2008; Ursu *et al.*, 2009; C. Wall, 3rd and Kentala, 2005; C. Wall, III and Weinberg, 2003; C. I. I. I. Wall *et al.*, 2004).

The Mobile Instrument for Motion Instruction and Correction (MIMIC) enables an expert (such as a physical therapist) to map his/her movements to a trainee in hands-free fashion. In a proof-of-concept study, we found that expert-subject cross-correlation values were maximized and time delays and average position errors were minimized when a 0.5 degree position error threshold and proportional plus half derivative control signal were used (Lee and Sienko, 2010). This study builds on our prior work by assessing further benefits derived from the addition of visual feedback to the existing vibrotactile instructional cues.

Method

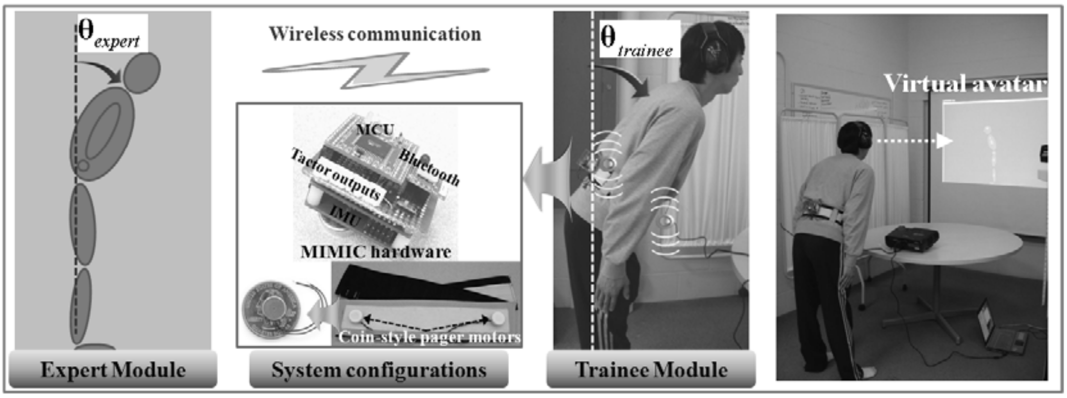

Figure 1. System configuration

The methods described herein are described in additional detail in (Lee and Sienko, 2010). An overall schematic representation of the MIMIC system is given in Figure 1. The wearable IMU-based expert-trainee motion error detection and vibrotactile instructional cuing device is composed of an Expert Module (EM) and a Trainee Module (TM). Each module includes a six degree-of-freedom inertial measurement unit (IMU), microcontroller unit (MCU), Bluetooth module, data saving module, and battery. The TM additionally has an array of tactors (coin-style eccentric mass pager motors) that provides vibrotactile stimulation to the skin. The expert’s body movements are sensed by the EM IMU and processed by an extended Kalman filter (EKF) (Welch and Bishop, 2005) estimation algorithm embedded in the MCU. The estimated expert motion is transmitted wirelessly to the TM via Bluetooth communication, and directional instructions are displayed via vibrotactile stimulation to the skin based on the computed difference between the expert and trainee motion. During trials involving visual feedback, a virtual 3D avatar is used as shown in Figure 1.

Five young (23.4±3.3 years) healthy naïve subjects (3 male, 2 female) participated in the study. University of Michigan Institutional Review Boards approved the experimental protocol, which conformed to the Helsinki Declaration. Informed consent was obtained from each subject prior to the start of the experiment.

Subjects (i.e. trainees) were instrumented with the TM and instructed to 1) stand with their feet parallel approximately 15cm apart (indicated by floor markings) and 2) "move in the direction of the vibration until the vibration stops". Standard foam earplugs and earmuffs were provided to eliminate environmental and tactor noise. Tactors were placed on the trunk midline (navel and spine) at approximately the L4/L5 lumbar level of the spine.

Subjects were asked to replicate the previously recorded expert anterior-posterior (A/P) trunk motion by following 1) vibrotactile instructional cues alone, 2) visual instructional cues alone, or 3) combined vibrotactile and visual instructional cues. The expert motion consisted of an anterior 20° trunk bend followed by a 6s static hold at 20° and a posterior trunk bend to return to neutral upright stance. The anterior and posterior 20° trunk bends were performed at a rate of approximately 1.12 deg/s. All trials were performed with eyes open except for vibrotactile alone trials. Note that each subject was asked to bend only at the waist in response to three different instructional cues while they were performing the task. For the vibrotactile instructional cues, 0.5 degree position error threshold and proportional plus half derivative control signal were used (Lee and Sienko, 2010). Each subject performed four repetitions of the each instructional modality, totaling twelve trials. The presentation of trial type was randomized and no practice trials were provided. In addition, pre-/post-baseline data were collected to assess any potential training effects.

To characterize the subjects' ability to replicate the expert motion, a cross correlation analysis of the expert and subject trunk tilt angle was performed. The output of the cross correlation analysis was normalized between 0 and 1, with 1 indicating perfectly matched motion. Measured time delay was also used to assess motion replication, with a positive delay indicating a time lag between the trainee and expert motion. Average position error between the expert and the subject was also computed. Non-parametric Kruskal–Wallis one-way analysis of variance was performed using PASW (SPSS, Inc.), with each instructional modality (vibrotactile, visual, combined vibrotactile+visual) as an independent variable and cross correlation value (0 to 1), time delay (τ), and position error as dependent variables. Significance was defined at the $p<0.05$ level.

Results

Preliminary results showed that subjects maximized cross correlation values and minimized delays and position errors when using a combination of visual and vibrotactile instructional cues. The average cross correlation values for trials involving combined vibrotactile and visual cues (0.98) and vibrotactile cues alone (0.98) were significantly higher than the visual cues alone (0.85) (Figure 2(a)). In addition, subjects had significantly smaller position errors when replicating the expert motion with combined vibrotactile and visual instructional cues (0.27 deg) compared to either vibrotactile (0.34 deg) or visual (2.05 deg) instructional cues alone (Figure 2(b)). The time delay was significantly larger for subjects given a visual cue alone (0.95 s) versus either the vibrotactile cue alone (0.20 s) or combined vibrotactile and visual (0.14 s) instructional cues.

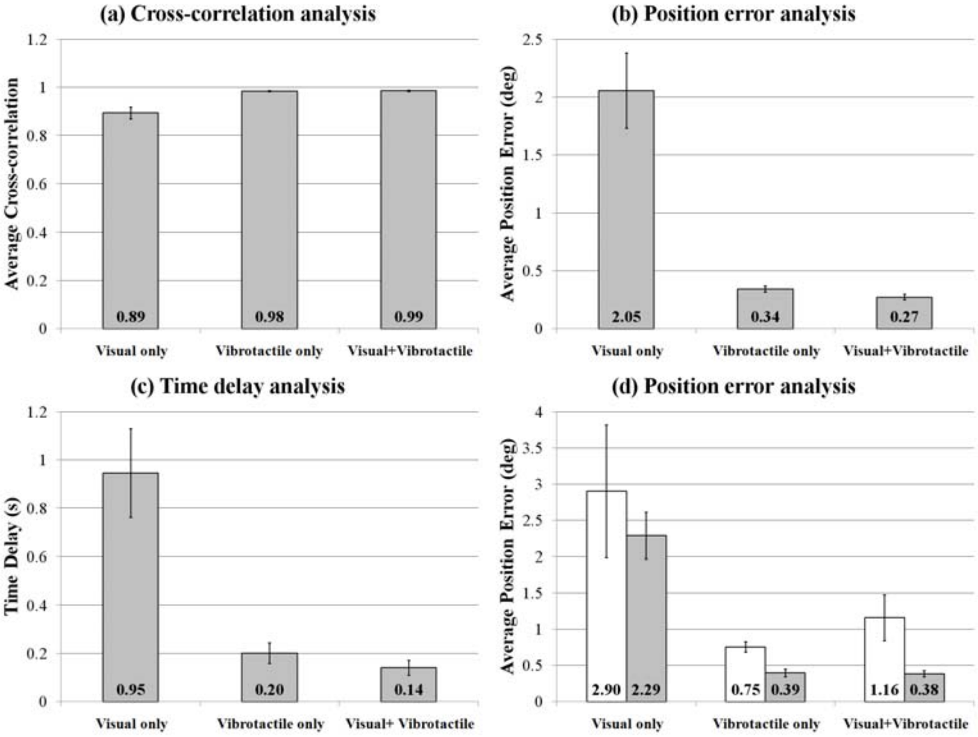

Figure 2. Preliminary results: (a) Expert-trainee cross-correlation; (b) expert-trainee position error; (c) expert-trainee time delay; and (d) expert-trainee position error pre/post experiment. Error bars represent standard error of mean.

Summary and disclaimer

This paper describes the effects of multimodal instructional cues on subjects' ability to replicate expert motion while using the MIMIC system. We describe a wearable device for real-time motion error detection and vibrotactile instructional cuing that enables experts to wirelessly map their body motion to one or more trainees. The MIMIC has potential applications in both physical therapy settings and the athletic arena; it may also be used by an individual at home to perform balance-rehabilitation exercises either previously recorded in the presence of a physical therapist or distributed via the internet. Additionally, it may be used to simultaneously instruct a classroom of trainees.

The main advantage of this design over other motion replication systems such as described in Lieberman (Lieberman and Breazeal, 2007) or Kapur (Kapur *et al.*, 2009) is that the IMUs eliminate the need for any external apparati such as mechanical links, cameras, or magnetic emitters that are characteristic of mechanical, optical, and electromagnetic tracking systems.

Based on the results of this proof-of-concept study, we demonstrated that subjects could best replicate the relatively simple task of bending at the waist using combined vibrotactile and visual instructional cues based on expert-trainee position error. Their position error in this case was better than that achieved using either vibrotactile or visual feedback conditions alone. In the case of visual instructional cue, the average of position error from all subjects was significantly higher than other instructional cues such as tactile only or combined of visual and tactile. However, combined vibrotactile plus visual instructional cues were not significantly better for replicating the expert motion compared to vibrotactile cues alone. Therefore, it could be argued that a simpler system involving vibrotactile cues alone is sufficient for slow and simple motion replication tasks. It remains to be seen the extent to which motion can be mimicked when multiple body segments receive instructional cues and the motion is faster.

Acknowledgement

This work was supported by the University of Michigan Office of Technology Transfer and the National Science Foundation's CAREER program (RAPD-0846471, funded under the American Recovery and Reinvestment Act of 2009).

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