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Visuomotor Discordance in Virtual Reality: Effects on Online Motor Control

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Abstract

Virtual reality (VR) applications are rapidly permeating fields such as medicine, rehabilitation, research, and military training. However, VR-induced effects on human performance remain poorly understood, particularly in relation to fine-grained motor control of the hand and fingers. We designed a novel virtual reality environment suitable for hand-finger interactions and examined the ability to use visual feedback manipulations in VR to affect online motor performance. Ten healthy subjects performed a simple finger flexion movement toward a kinesthetically-defined 45° target angle while receiving one of three types of VR-based visual feedback in real-time: veridical (in which the virtual hand motion corresponded to subjects' actual motion), or scaled-down / scaled-up feedback (in which virtual finger motion was scaled by 25% / 175% relative to actual motion). Scaled down- and scaled-up feedback led to significant online modifications (increases and decreases, respectively) in angular excursion, despite explicit instructions for subjects to maintain constant movements across conditions. The latency of these modifications was similar across conditions. These findings demonstrate that a VR-based platform may be a robust medium for presenting visuomotor discordances to engender a sense of ownership and drive sensorimotor adaptation for (re)training motor skills. This may prove to be particularly important for retraining motor skills in patients with neurologically-based movement disorders.

I. Introduction

The effects of visual feedback on the human motor system can be profound. Indeed, the simple act of action observation has been shown to significantly boost the motor system [1–11], facilitating training and encoding motor memories in both healthy subjects and patients with neurological diseases. Results of these studies also suggest that action observation of one's own movement during training is required to appropriately augment behavior and expedite learning [7]. Even more interesting are studies that demonstrate subjects' tendency to dynamically tune behavior, in real-time, to movements performed by anthropomorphically-shaped objects that not only appear "lifelike" but also move in a manner that resembles normal human motion [12, 13]. This work has served as a driving force for development of technologies that allow researchers and clinicians to utilize different forms of visual feedback, time-locked to subjects' own movements, as a means of investigating the effects of feedback on the motor system, as well as a means of delivering therapy to patients.

It has been suggested that VR environments will become mainstay in neurorehabilitation. VR gives subjects a sense of realness that can approximate real-world settings, while allowing the experimenter to modify visual parameters. The experimenter has full control over the size, shape, color, displacement, and velocity of objects in the virtual environment, which allows for controlled alteration of visual feedback during a motor task. Importantly, VR allows for an enjoyable, interactive setting that is conducive for training. For example, numerous prior studies demonstrate the efficacy of VR therapy in stroke rehabilitation [14–18], and VR behavioral effects have been shown not only to outlast training, but also to generalize across similar, though unpracticed, motor tasks [19]. VR therefore is an ideal instrument for providing augmented visual feedback.

The scope of this study was twofold. First, we present the design of a novel virtual reality (VR) environment developed by our team, that integrates lifelike VR hands with real-time acquisition of hand kinematics. Second, we present experimental data that demonstrate how altering visual motion of the VR hand models, thus inducing a visuomotor discordance time-locked to the subjects' own motor commands, can alter online motor performance. Finally, we discuss these findings in the context of how this approach may be useful in the basic and clinical sciences to study and rehabilitate the motor system.

Augmenting visual feedback during movement can be used to induce a visuomotor discordance such that the visual perception of one's movement does not coincide with the intended action and proprioceptive feedback. Often, visuomotor discordance is studied by rotating the motion of a cursor in a two dimensional plane that is often orthogonal to the actual movement. Furthermore, these experiments generally focus on gross upper limb movements, rather than dexterous hand and finger motion (grasping, pinching, pointing, individuation and sequencing). For these reasons, we focus on studying feedback effects on online hand coordination.

We chose to study visuomotor discordance by imposing a gain perturbation to the VR hand model. Visuomotor gain (as opposed to rotation perturbations) is generally more apt to learning, and is more amenable to generalization [20–23]. For these reasons, it offers an ideal starting point for a systematic investigation of the effects of visual feedback on motor performance. We hypothesized that applying a down-scaled gain would lead subjects to over-compensate by increasing their movement vigor, while applying an up-scaled gain would lead subjects to reducing their movement vigor. Our long-term goal is to use this knowledge to develop a versatile VR platform that will serve as a tool for neurorehabilitation.

II. Methods

A. Subjects

Ten healthy right-handed [24], subjects (7 male, mean ±1 standard deviation [SD]: 27.5+/−6.7 years old) without history of neurological disease or orthopedic hand impairment participated in the study after signing institutionally informed consent.

B. Virtual Reality (VR) Environment

Subjects donned kinematic datagloves (5DT Data Gloves, Fifth Dimension Technologies), which were calibrated for each subject. Subjects were seated with hands and wrists comfortably supported in a semi-pronated position and hidden from direct line-of-sight underneath a flat screen monitor. A VR interface was constructed using Virtools Software (Dassault Systems), which permitted real-time streaming of kinematic data from the gloves. To maximize the perception of realness, the display was positioned horizontally above the hands and angled so that the vantage point of the virtual hands, whose movement was driven by glove data, corresponded to that of the subjects' actual hands just beneath the monitor (Fig. 1). Our published and preliminary data suggest that our VR environments engender a sense of realness to the subjects, provide valid and reliable measurement of kinematics, and hold promise as a rehabilitation tool in clinical populations [25–30].

C. Movement Task

When the cue-word 'Move' appeared on the monitor, subjects were instructed to flex the metacarpophalangeal (MCP) joint of their right index finger to a physical angle of 45°, then return to an initial fully-extended position. Subjects were instructed to move at a comfortable speed. On all trials, a visual cue (the virtual finger would turn red) was provided when subjects reached the 45° *physical* target angle, irrespective of *visual* feedback (see next section). Because the visual cue did not appear until the end of the trial, it was expected that subjects would overshoot the 45° target angle.

D. Visual Feedback Conditions

Visual discordance was provided by applying either a 25% (22 trials) or 175% (22 trials) scaling factor to the real-time kinematic data streaming from the dataglove, and then applying the scaled data to actuate the virtual hand. Thus, each virtual joint moved 0.25 or 1.75 degrees, respectively, for every degree of actual joint motion. Veridical visual feedback (22 trials, control condition) was also provided by applying a 100% scaling factor to the VR hands. All 66 trials were pseudo-randomly interleaved in one 6.6 minute block.

E. Analysis

Joint angle data was acquired (rate, 50Hz) and analyzed offline. Data was filtered (10 Hz low-pass 2nd order Butterworth) using custom MATLAB software (The Mathworks, Inc.). Movement onset and offset were defined as the time when angular velocity exceeded and fell below, respectively, 5% of peak angular velocity. Peak joint angle (degrees) between movement onset and offset was the dependent kinematic variable. Means were calculated for each subject and each condition and submitted to a one-way repeated measures analysis of variance (rmANOVA) with factor "Condition" and levels "25% Gain""175% Gain", and "100% Veridical". We also analyzed a measure of latency, defined as the time after movement onset when kinematic traces in the 25% and 175% conditions deviated from the mean ±1 SD of the veridical (100%) trace. This measure indicated the time at which the compensatory response to the visuomotor gain perturbation was evident at the kinematic level. Statistical significance was set at 0.05.

III. Results

For each subject, joint angle traces were aligned according to movement onset, averaged across the 22 trials of each condition, and plotted. Fig. 2 demonstrates that, for most subjects, the mean traces in the 25% (red) and 175% (green) scaling conditions exceeded and fell below, respectively, the mean veridical trace (blue). Each subject's mean traces were averaged and plotted as a global joint angle trace, at the group level (Fig. 2, bottom). The group-level joint angle trajectories revealed a pattern consistent with those evident at the individual subject level. Group mean joint excursion in the 25%, 100%, and 175% scaling conditions were 63.8°, 58.1°, and 53.6°, respectively (Fig. 3, left). Repeated measures ANOVA revealed a significant ($F_{2,29}$= 24.268, p<0.001) effect of visual feedback on peak angle, and post-hoc pairwise comparisons showed that peak amplitude was significantly different between the 25% and 100% scaling conditions (t_9=3.654, p=0.005) and between the 175% and 100% scaling conditions (t_9=5.490, p<0.001).

As an additional post-hoc sub-analysis, we explored latency of deviation among the joint angle trajectories. This measure characterized the time at which the compensatory response to the visuomotor gain perturbation was evident at the kinematic level. Latency was defined as the time after movement onset when kinematic traces in the 25% and 175% conditions deviated from the mean ±1 SD veridical (100%) trace. Latency for the 25% scaling condition was calculated as the time when the trace exceeded one standard deviation above the mean veridical trace. Latency for the 175% scaling condition was calculated as the time when the trace fell below one standard deviation of the mean veridical trace. Mean latencies for each subject and each condition were recorded, and a group average was calculated for both the 25% scaling condition (group mean ±1SEM: 0.41 ± 0.038 seconds) and the 175% scaling condition (0.38 ±0.031 seconds) (Fig. 3, right). A paired t-test revealed no significant differences in compensatory latency between the 25% and 175% scaling groups (t_9=0.739, p=0.478).

IV. Discussion

The results of this experiment demonstrate the efficacy of our VR environment as a tool for altering online motor performance. While performing movements under visual gain perturbations, subjects adjusted their kinematics in a predicable manner (specific to each type of perturbation) as a means of compensating for the visuomotor discordance. We interpret these data in the following way. During downscaled (25% gain) trials, visual feedback provided the false illusion that motor output was inappropriately low. Consequently, the motor system compensated by increasing output drive to the muscles, leading to greater movement (angular excursion) in an attempt to match the virtual angle to the preplanned angle. Conversely, in the up-scaled (175% gain) trials, the exact opposite occurred – the illusion that the original motor plan was overly robust led subjects to decrease motor drive, resulting in reduced angular excursion.

Recent evidence suggests that visuomotor *gain*relative to visuomotor rotation, exhibits broader generalization to untrained movement trajectories [22]. Prior studies have also shown that motor learning following *online* (real-time) visuomotor rotation exhibits broader generalization, relative to performance changes following offline error feedback [31, 32]. However, these studies implement visuomotor perturbations via virtual cursors, rather than *lifelike hand models*. Here, we have integrated these modalities, demonstrating that scaled visual feedback of human finger movement, displayed in a VR environment, alters motor performance in a predictable manner.

The ability to shape online movement kinematics is a valuable tool in neurorehabilitation. For example, stroke patients often have impaired proprioception and may tend to undershoot targets during particular training paradigms. By applying a down-scaled visual gain to their environment, the results of the current experiment suggest that subjects might increase excursion to the target goal. In other words, the illusion of excessive underperformance may boost the motor system, resulting in more vigorous performance. It would be interesting to determine whether, over many trials, the subject maintains accuracy even if visual gain is gradually increased towards veridical (i.e. increasing the gain from 25% to 100%). If true, the long-term goal would be to establish individualized rehabilitation training protocols for patients, protocols that are tailored to patients' range of motion and degree of impairment.

Finally, another interesting finding in this experiment was that latencies in the scaled-down and scaled-up visual feedback conditions were similar. This suggests that latency may be dependent not on the direction of gain (i.e. scaled-down versus scaled-up) but rather on the magnitude of visuomotor discordance, relative to veridical feedback. Even more interesting is whether the relationship between altered motor performance and visuomotor discordance is linear (i.e. whether motor command increases proportionately as visual gain is brought from 100% to 25%). Furthermore, if performance is related to the degree of discordance, then one would also hypothesize that a threshold gain level may exist. In future experiments, we hope to determine the visual gain tuning function that characterizes the threshold for perceiving visuomotor discordance.

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REFERENCES

1. Rizzolatti G, et al. Premotor cortex and the recognition of motor actions. Brain Res Cogn Brain Res. 1996 Mar.vol. 3:131–141. [PubMed: 8713554]
2. Gallese V, et al. Action recognition in the premotor cortex. Brain. 1996 Apr; vol. 119(Pt 2):593–609. [PubMed: 8800951]
3. Fadiga L, et al. Motor facilitation during action observation: a magnetic stimulation study. J Neurophysiol. 1995 Jun.vol. 73:2608–2611. [PubMed: 7666169]
4. Aziz-Zadeh L, et al. Lateralization in motor facilitation during action observation: a TMS study. Exp Brain Res. 2002 May.vol. 144:127–131. [PubMed: 11976767]
5. Celnik P, et al. Encoding a motor memory in the older adult by action observation. Neuroimage. 2006 Jan 15.vol. 29:677–684. [PubMed: 16125417]
6. Kilner JM, Frith CD. A possible role for primary motor cortex during action observation. Proc Natl Acad Sci U S A. 2007 May 22.vol. 104:8683–8684. [PubMed: 17502595]
7. Celnik P, et al. Effects of action observation on physical training after stroke. Stroke. 2008 Jun.vol. 39:1814–1820. [PubMed: 18403746]
8. Stefan K, et al. Formation of a motor memory by action observation. J Neurosci. 2005 Oct 12.vol. 25:9339–9346. [PubMed: 16221842]
9. Stefan K, et al. Concurrent action observation modulates practice-induced motor memory formation. Eur J Neurosci. 2008 Feb.vol. 27:730–738. [PubMed: 18279325]
10. Strafella AP, Paus T. Modulation of cortical excitability during action observation: a transcranial magnetic stimulation study. Neuroreport. 2000 Jul 14.vol. 11:2289–2292. [PubMed: 10923687]
11. Alaerts K, et al. Is the human primary motor cortex activated by muscular or direction-dependent features of observed movements? Cortex. 2009 Nov-Dec;vol. 45:1148–1155. [PubMed: 19100971]
12. Kilner JM, et al. An interference effect of observed biological movement on action. Curr Biol. 2003 Mar 18.vol. 13:522–525. [PubMed: 12646137]
13. Kilner J, et al. Interference effect of observed human movement on action is due to velocity profile of biological motion. Soc Neurosci. 2007; vol. 2:158–166. [PubMed: 18633814]
14. Merians AS, et al. Virtual reality-augmented rehabilitation for patients following stroke. Phys Ther. 2002 Sep.vol. 82:898–915. [PubMed: 12201804]
15. Adamovich SV, et al. A virtual reality based exercise system for hand rehabilitation post-stroke: transfer to function. Conf Proc IEEE Eng Med Biol Soc. 2004; vol. 7:4936–4939. [PubMed: 17271420]
16. Deutsch JE, et al. Development and application of virtual reality technology to improve hand use and gait of individuals post-stroke. Restor Neurol Neurosci. 2004; vol. 22:371–386. [PubMed: 15502277]
17. Jang SH, et al. Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: an experimenter-blind preliminary study. Arch Phys Med Rehabil. 2005 Nov.vol. 86:2218–2223. [PubMed: 16271575]

18. You SH, et al. Virtual reality-induced cortical reorganization and associated locomotor recovery in chronic stroke: an experimenter-blind randomized study. Stroke. 2005 Jun.vol. 36:1166–1171. [PubMed: 15890990]
19. Holden MK. Virtual environments for motor rehabilitation: review. Cyberpsychol Behav. 2005 Jun.vol. 8:187–211. discussion 212–9. [PubMed: 15971970]
20. Krakauer JW, et al. Learning of visuomotor transformations for vectorial planning of reaching trajectories. J Neurosci. 2000 Dec 1.vol. 20:8916–8924. [PubMed: 11102502]
21. Pine ZM, et al. Learning of scaling factors and reference axes for reaching movements. Neuroreport. 1996 Oct 2.vol. 7:2357–2361. [PubMed: 8951852]
22. Pearson TS, et al. Learning not to generalize: modular adaptation of visuomotor gain. J Neurophysiol. 2010 Jun.vol. 103:2938–2952. [PubMed: 20357068]
23. Paz R, et al. Acquisition and generalization of visuomotor transformations by nonhuman primates. Exp Brain Res. 2005 Feb.vol. 161:209–219. [PubMed: 15480596]
24. Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia. 1971 Mar.vol. 9:97–113. [PubMed: 5146491]
25. Adamovich SV, et al. Sensorimotor training in virtual reality: a review. NeuroRehabilitation. 2009; vol. 25:29–44. [PubMed: 19713617]
26. Adamovich SV, et al. Design of a complex virtual reality simulation to train finger motion for persons with hemiparesis: a proof of concept study. J Neuroeng Rehabil. 2009; vol. 6:28. [PubMed: 19615045]
27. Merians AS, et al. Virtual reality to maximize function for hand and arm rehabilitation: exploration of neural mechanisms. Stud Health Technol Inform. 2009; vol. 145:109–125. [PubMed: 19592790]
28. Adamovich SV, et al. A virtual reality-based system integrated with fmri to study neural mechanisms of action observation-execution: a proof of concept study. Restor Neurol Neurosci. 2009; vol. 27:209–223. [PubMed: 19531876]
29. Adamovich S, et al. Recovery of hand function in virtual reality: Training hemiparetic hand and arm together or separately. Conf Proc IEEE Eng Med Biol Soc. 2008; vol. 2008:3475–3478. [PubMed: 19163457]
30. Merians AS, et al. Innovative approaches to the rehabilitation of upper extremity hemiparesis using virtual environments. Eur J Phys Rehabil Med. 2009 Mar.vol. 45:123–133. [PubMed: 19158659]
31. Shabbott BA, Sainburg RL. Learning a visuomotor rotation: simultaneous visual and proprioceptive information is crucial for visuomotor remapping. Exp Brain Res. 2010 May.vol. 203:75–87. [PubMed: 20237773]
32. Shabbott BA, Sainburg RL. On-line corrections for visuomotor errors. Exp Brain Res. 2009 May.vol. 195:59–72. [PubMed: 19288090]

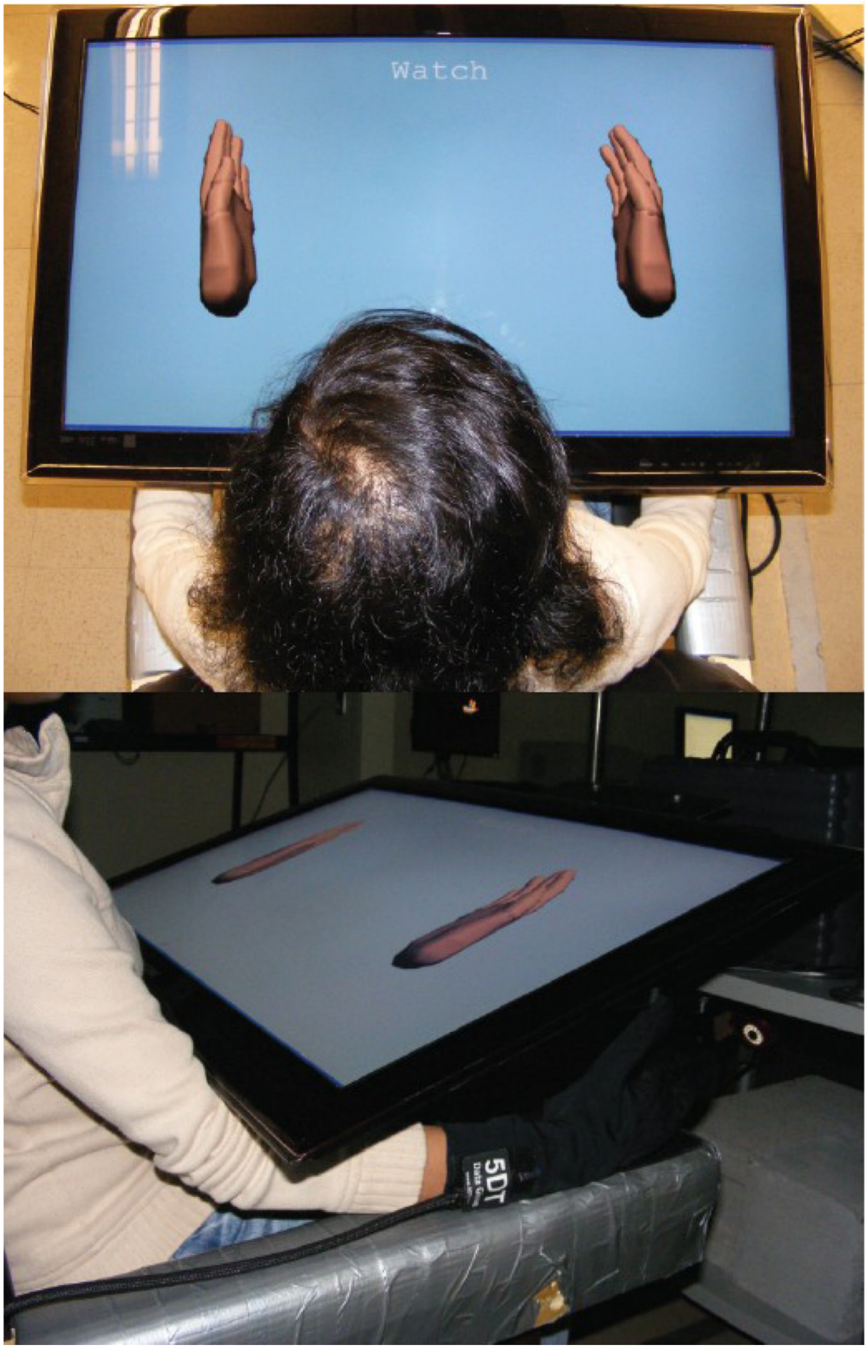

Fig. 1.
Experimental setup from top and side views.

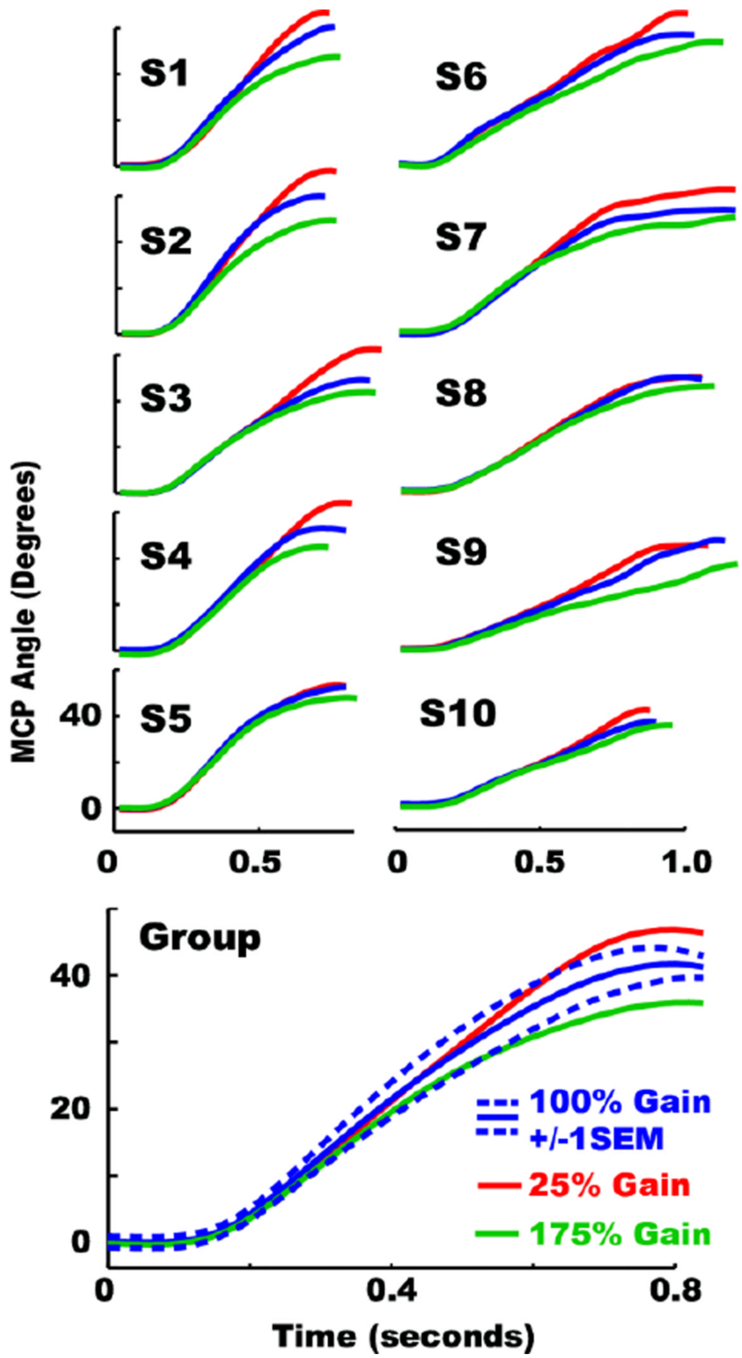

Fig. 2.

Top: Average kinematic traces across 22 trials, for each condition and subject (S1-S10). The 25%, 100%, and 175% scaling conditions are shown in red, blue, and green, respectively. *Bottom*: Group mean traces for each condition, averaged across all subjects. Dashed blue line represents veridical mean ± 1SEM.

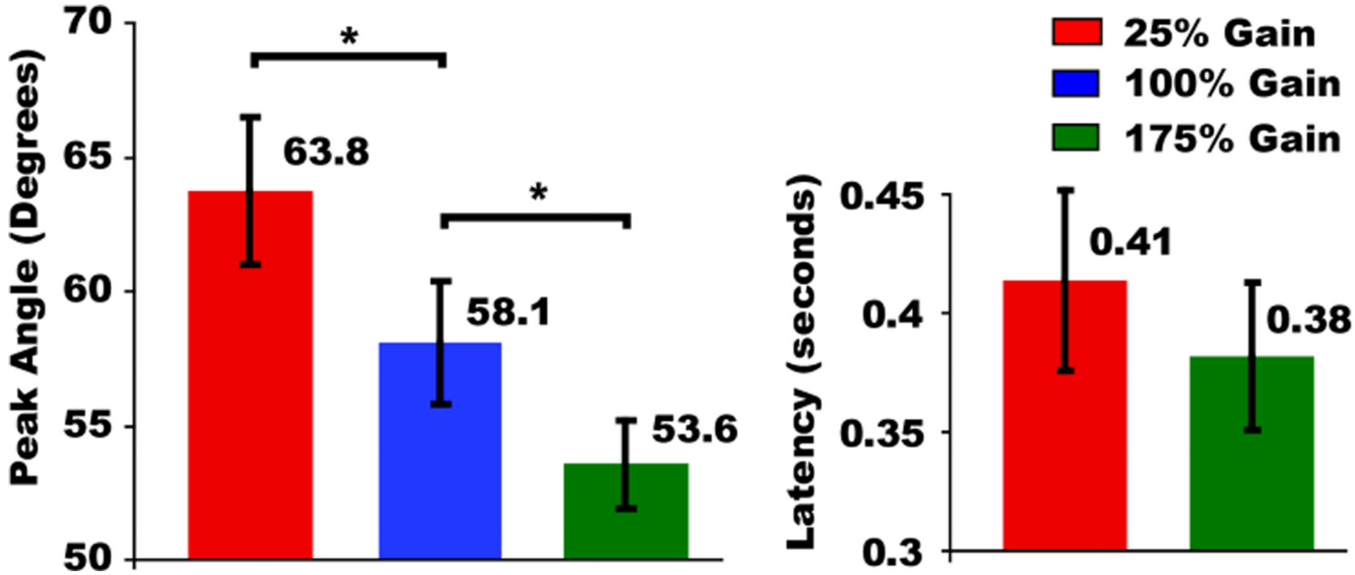

Fig. 3.

Group mean (±1SEM) peak angle (left) and latency (right). The three scaling conditions – 25%, 100% (control), and 175% – are shown in red, blue, and green, respectively. Asterisk denotes statistical significance.