Published in final edited form as:
IFMBE Proc. 2009 September ; 25(9): 335–338. doi:10.1007/978-3-642-03889-1_90.

Robot-amplified manual exploration improves load identification

F.C. Huang[1], **J.L. Patton**[2], and **F.A. Mussa-Ivaldi**[3]

[1]Sensory Motor Performance Program, Rehabilitation Institute of Chicago

[2]Bioengineering, University of Illinois at Chicago

[3]Physical Medicine and Rehabilitation, Mechanical and Biomedical Engineering, Northwestern University

Abstract

We tested how manual exploration with anisotropic loading (*Viscosity-Only* (negative), *Inertia-Only*, or *Combined-Load*) influenced skill transfer to the isolated inertial load. Intact subjects (N=39) performed manual exploration with an anisotropic load before evaluation with prescribed circular movements. Combined-Load resulted in lower error (6.89±3.25%) compared to Inertia-Only (8.40±4.32%) and Viscosity-Only (8.17±4.13%) according to radial deviation analysis (% of trial mean radius). An analysis of sensitivity to load variation in normal and catch trials reveals performance differences were likely due to changes in feedforward mass compensation. Analysis of exploration movement revealed higher average speeds (12.0%) and endpoint forces (22.9%) with *Combined-Load* exploration compared to *Inertia-Only*. Our findings suggest that free movements amplified by negative viscosity can enhance the ability to identify changes in inertial loading.

Keywords

manual control; systems modeling; error-augmentation

I. Introduction

When encountering an unfamiliar manual task, the type of movement pattern itself could influence the efficiency of learning. The motor system evidently exhibits some ability to generalize between prescribed movements[1]. Recent literature suggests that encouraging variability is as effective as repeated practice for generalizing skills in a ballistic task[2]. Other researchers note that practice variability may be especially effective if task parameters are expected to change[3], and can promote more stable performance[4]. Broad sensory-motor experiences associated with free exploration may facilitate the identification of environment dynamics[5]—a process critical for motor planning.

While free exploratory movements might offer richer sensory experiences, it is unclear if the learner necessarily knows how to take advantage of that freedom. Novel forms of human-machine interaction could offer a collaborative process of scaffolding or guiding movement, while enabling the individual to direct their own learning. One promising form of such interaction is movement amplification from robot amplified movement [6]-[7], though learning and generalization of motor skills under these conditions is not yet well understood.

For individuals with motor impairment, negative impedance could reduce workload while providing sensory-motor re-training. For healthy individuals, force fields presented during robotic training have already demonstrated dramatic adaptation in manual coordination with relatively brief exercise [8]-[9]. The challenge with any training paradigm is whether the individual can both learn and generalize learning to unpracticed conditions.

We conducted an investigation into how learning an inertial load might be supplemented with active impedance (negative viscosity). We examined how a period of free manual exploration with both negative viscosity and inertia can benefit performance when the viscosity is removed and only the inertial load remains. We compared the effectiveness of this training to training with an inertial load alone, and also compared it with training with negative viscosity training alone. Our findings demonstrate that exploratory training with negative viscosity improves learning and generalization by facilitating the process of identifying changes in loading conditions.

II. Methods

A. Apparatus and Implementation of Anisotropic Loads

We asked subjects to control the movement of a two-degree of freedom planar force-feedback device (Fig. 1) described elsewhere [8]. During the evaluation task, the handle responded as if it were a physical mass along one axis, while no load was present in the perpendicular axis. During training for some conditions, we included anisotropic negative viscosity loads aligned with the axis of the inertial load. We selected five orientations for the anisotropic loads: θ_m=0, 36, 72, 108, 144 degrees with respect to the frontal plane. End-point forces $F_x(t)$ and $F_y(t)$ approximating inertial and viscous loads were presented according to:

$$\begin{bmatrix} F_x(t) \\ F_y(t) \end{bmatrix} = R^t \begin{bmatrix} 0 & 0 \\ 0 & m \end{bmatrix} R \begin{bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{bmatrix} + R^t \begin{bmatrix} 0 & 0 \\ 0 & b \end{bmatrix} R \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{bmatrix} \text{ where } R = \begin{bmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{bmatrix}. \quad (1)$$

We chose a mass parameter *m* of 0 or 3 kg and a viscosity parameter *b* of either 0 or -10 N-s/m. With the rotation matrix R, various anisotropic loads were selected representing orientations of load.

In this study 26 healthy individuals volunteered and were randomly assigned to either the *Inertia-Only* or *Combined-Load* subject groups. We later included a third group with 13 healthy individuals as a part of the *Viscosity-Only*.

Subjects were asked to perform two tasks using the robotic manipulandum: (1) training with free exploratory movements (*free exploration*) followed by (2) performance of a prescribed circular movement (*performance evaluation*). During free exploration, subjects were instructed to move the object at their discretion using various directions, speeds, and positions within a circular region (0.1 m radius centered within the workspace). The computer signaled the user to halt free exploration after 15 meters of handle end-point total travel. The experiment groups differed in terms of the loading conditions presented during free exploration.

Author Manuscript

Author Manuscript

Author Manuscript

During performance evaluation (2), subjects were instructed to move the robotic interface in three complete counter-clockwise revolutions at about 1 revolution per second. Subjects were told to achieve accurate and smooth performance as much as possible in circular movements about a target track (0.1 m radius). During normal trials, the performance evaluation included the same inertial load as that presented during the free exploration stage. However, the viscosity term (Eq-1) was set to zero during performance for all trials. In some instances, *catch trials* were presented, in which the loading was removed covertly.

III. Results

A. Differences in Evaluation

Results from ANOVA of Evaluation trials indicated influences from each experiment factor: subject group ($F[2, 1800] = 28.57$, $MSE = 0.04037$, p= 6.12e-13), load type ($F[4, 1800] = 9.91$, $MSE = 0.01401$, p=6.2e-8), and trial sequence ($F[9, 1800] = 8.81$, $MSE = 0.01245$, p=4.5e-13). Interactions were significant for the group-by-load effect ($F[8, 1800] = 5.15$, $MSE = 0.00728$, p=2.3e-6) and the group-by-trial effect ($F[18, 1800] = 2.88$, $MSE = 0.00408$, p=4.6e-3). These findings indicate that load orientations differed in difficulty, and some performance changes occurred over the course of performance trials following free exploration, though these effects depended on subject group. In contrast, results from ANOVA for catch trials indicated a strong influence only for effects from load type ($F[4, 368] = 20.0$, $MSE = 0.0318$, p=6.4e-14) and trial sequence ($F[1, 368] = 9.5$, $MSE = 0.1511$, p=2.2e-3). Interactions were not significant for catch trials. These results suggest that subject groups had similar sensitivity to unexpected loads, and that this sensitivity changes between the first and second catch trials.

Including free exploration with combined inertia and negative viscosity resulted in lowest overall error. According to the mean radial deviation metric (% of mean trial radius), the *Combined-Load* training group exhibited 18.0% lower error (6.89±3.25, mean and SD) compared to *Inertia-Only* (8.40±4.32, mean and SD) and 14.2% lower compared to *Viscosity-Only* (8.03±4.13, mean and SD). The Inertia-Only exhibited 4.64% lower radial deviation relative to Viscosity-Only. According to Tukey HSD post-hoc tests, these differences were significant for Combined-Load compared to Inertia-Only (1.51; CI:1.00, 2.02; p=5.0e-11) and compared to the Viscosity-Only group (1.14; CI: 0.62, 1.65; p=5.4e-7). Differences between Viscosity-Only and Inertia-Only were not significant (0.37; CI: 0.14, 0.88; p=0.20).

Noting a cyclic pattern of error (see Fig. 2), we fit sinusoids for the radial magnitude as a function of load orientation and observed non-significant amplitude from *Combined-Load* (mean 0.0058, CI:-0.0021, 0.0136, R^2=0.0165). In contrast, both *Inertia-Only* (mean 0.0166, CI: 0.0062, 0.0270, R^2=0.0725) and *Viscosity-Only training* (mean 0.0313, CI: 0.0168, 0.0455, R^2=0.1270) exhibited significant non-zero amplitudes. Low sensitivity to load changes could indicate increased co-contraction or stiffness control. However, analysis of catch-trial results indicates similarity sensitivity to unexpected absence of loading, which suggests that the appropriate feedforward strategy was available for both the *Combined-Load* and *Inertia-only* groups.

B. Analysis of Exploration Behavior

In addition to trends in Evaluation trials, we also observed key differences between the subject groups in free exploration behavior, which show that including negative viscosity promoted a wider range of dynamics. Histograms (Fig. 3, left) of the speed and forces (absolute value of components along direction of anisotropy major axis) averaged over all subjects and trials observed during free exploration showed that the Combined-Load training group exhibited a diminished peak at low values in favor of a wider range of values. Similar trends were observed for acceleration, though the differences were not significant. No differences were observed for position states, indicating similar spatial extents of exploration between groups. Similarly, no differences were observed for movement states and forces in the no-load axis (orthogonal to the inertial load).

A comparison of mean speed and endpoint force data observed during the exploration stages (Fig. 3, right) indicate greatest activity from the Combined-Load group. Using Tukey's post-hoc tests for significant differences, we found that the average speed was 12.0% larger for the Combined-Load group compared to the Inertia-Only group (0.036 m/s; CI: 0.002, -0.070; p=0.038), but was 18.8% smaller with respect to the Viscosity-Only group (-0.077 m/s; CI: -0.111, -0.042; p=8.37e-7). The Inertia-Only group also exhibited 37.9% smaller average speed compared to the Viscosity-Only group (0.112 m/s; CI: 0.078, 0.147; p=1.24e-12). In contrast to the trends in speed, we found that the average force was largest for the Combined-Load training group: 22.9% greater compared to the Inertia-Only group (1.27 N; CI: 0.42, 2.11; p=7.99e-15) and 179.0% greater compared to the Viscosity-Only training group (4.36 N; CI: 3.51, 5.20; p=1.46e-3). The Viscosity-Only group exhibited 55.9% smaller average force compared to the Inertia-Only group (-3.09 N; CI: -3.94, -2.25; p=4.24e-14). These trends suggest a greater similarity in training for the two groups that experience inertial loading during free exploration, with a somewhat increased range of exploration for the Combined-Load training group.

IV. Discussion

Our findings demonstrate that training with negative viscosity can improve learning of a passive object manipulation task, achieving even better performance than training with the passive conditions alone. These findings suggest a two-part process of improved load identification through enhanced sensorimotor experiences and successful generalization between mechanical environments. Negative viscosity evidently alters the efficiency of internal model formation of inertial loading by promoting broader exploration during training (See Fig. 3). We argue then that the motor system is able to transfer the enhanced motor scheme to the passive environment by relating the shared features between environments. These findings offer an intriguing new method for facilitating sensorimotor adaptation through augmentation with negative impedance.

Beyond preserving the formation of a feedforward scheme, we argue that including negative impedances can strengthen the learning of passive loading. Negative viscosity effectively introduces a form of error augmentation since it amplifies intended movements. Such environments presumably facilitate learning by strengthening the associations between motor actions and sensory consequences [10-11]. In contrast to perceptual changes, however, altering the force-motion sensitivity through mechanics necessitates changes in the energetic requirements and stability—important factors in promoting motor adaptation. Inertial characteristics of objects and the arm evidently influence preferred movements [12]. Schaal et al. (1996) [13] noted that in ball bouncing, the human motor system seems to autonomously adjust control towards a stable strategy. In these cases, the sensitivity of movement to motor input can be attributed to the impedance at the interface between the arm and environment, which will clearly influence how easily sensory-motor associations are learned.

Our analysis of free exploration movements confirm that including negative viscosity increased the range of experienced speeds and forces—a result that could explain how the *Combined-Load* training group acquired more accurate compensation schemes. The distinct task stages presented in this study may have acted as contextual cues to facilitate switching of strategy elements[14]. Further study is needed to understand how switching between exploratory and prescribed movements influences skill transfer between environments with overlapping mechanical properties.

Enhancing motor learning by including negative impedances could have important implications to rehabilitation and other motor skill training endeavors. Loads that reduce workload[15] may be especially important for individuals with motor impairment who are prone to fatigue or have limited movement capabilities. The current study demonstrates the capacity of the motor system to train with a negative impedance, essentially a form of energetic assistance, and then successfully apply learned skills to a completely passive environment. Further study is needed to determine how training with negative impedance influence long term skill acquisition.

Acknowledgments

This work was supported by NINDS grant NS357673 and by the Coolidge Foundation.

References

1. Conditt MA, Mussa-Ivaldi FA. Central representation of time during motor learning. PNAS. 1999; 96(20):11 625–11 630. [PubMed: 9874762]
2. Shoenfelt EL, Snyder LA, Maue AE, McDowell CP, Woolard CD. Comparison of constant and variable practice conditions on free-throw shooting. Percept Mot Skills. Jun; 2002 94(3 Pt 2):1113–23. [PubMed: 12186232]
3. Shea C, Lai Q, Wright D, Immink M, Black C. Consistent and variable practice conditions: effects on relative and absolute timing. J Mot Behav. Jun; 2001 33(2):139–52. [PubMed: 11404210]
4. Giuffrida C, Shea J, Fairbrother J. Differential transfer benefits of increased practice for constant, blocked, and serial practice schedules. J Mot Behav. Dec; 2002 34(4):353–65. [PubMed: 12446250]
5. Huang FC, Gillespie RB, Kuo AD. Visual and haptic feedback contribute to tuning and online control during object manipulation. J Mot Behav. May; 2007 39(3):179–93. [PubMed: 17550870]
6. Kazerooni, H. Journal of Robotics and Autonomous Systems. Vol. 19. Elsevier; 1996. The Human Power Amplifier Technology at the University of California, Berkeley; p. 179-187.
7. Aguirre-Ollinger, Gabriel; Colgate, J Edward; Peshkin, Michael A.; Goswami, Ambarish. A 1-DOF assistive exoskeleton with virtual negative damping: effects on the kinematic response of the lower limbs. IROS. 2007:1938–1944.

8. Patton JL, Mussa-Ivaldi FA. Robot-assisted adaptive training: custom force fields for teaching movement patterns. Biomedical Engineering, IEEE Transactions on. 2004; 51(4):636–646.

9. Patton JL, Stoykov M, Kovic M, Mussa-Ivaldi FA. Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors. EBR. 2006; 168:368–383.

10. Matsuoka Y, Brewer B, Klatzky R. Using visual feedback distortion to alter coordinated pinching patterns for robotic rehabilitation. J of NeuroEngineering and Rehabilitation. 2007; 4(1):17.

11. Wei, Y.; Bajaj, P.; Scheidt, R.; Patton, JL. Visual Error Augmentation for Enhancing Motor Learning and Rehabilitative Relearning; IEEE Int. Conference on Rehabilitation Robotics; Chicago, IL. 2005;

12. Sabes PN, Jordan MI, Wolpert DM. The Role of Inertial Sensitivity in Motor Planning. J Neurosci. 1998; 18(15):5948–5957. [PubMed: 9671681]

13. Schaal S, Sternard D, Atkeson CG. One-handed juggling: A dynamical approach to rhythmic movement task. Journal of Motor Behavior. 1996; 2(28):165–183. [PubMed: 12529218]

14. Krouchev NI, Kalaska JF. Context-Dependent Anticipation of Different Task Dynamics: Rapid Recall of Appropriate Motor Skills Using Visual Cues. J Neurophysiol. 2003; 89(2):1165–1175. [PubMed: 12574490]

15. Housman, S.; Le, V.; Rahman, T.; Sanchez, R.; Reinkensmeyer, D. Arm-training with t-wrex after chronic stroke: Preliminary results of a randomized controlled trial; Proceedings of the 2007 IEEE 10th International Conference on Rehabilitation Robotics; Noordwijk, Netherlands. Jun 12-15. p. 562-568.

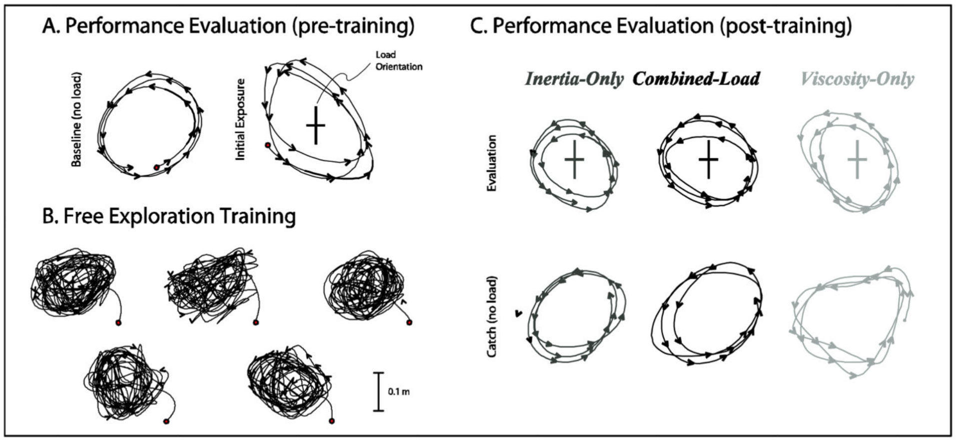

Fig. 1.

Typical handle trajectories from one subject during evaluations for one load condition. Coloring (red to blue) indicates time progression. (A) Curvature is most consistent in the Baseline (no load) condition. Systematic distortions arise during Initial Exposure with unexpected anisotropic inertial loading. (B) For each load, subjects were presented with a free exploration stage prior to performance evaluation. Trajectories for each load orientation (indicated by longer black line) of anisotropic inertia reveal wide variability. (C) Trajectories for Evaluation and Catch trials demonstrate error patterns between groups. Errors in Evaluation trials typically were less than Initial Exposure. In contrast, unexpected Catch (no load) trials exhibit systematic errors of similar magnitude with respect to Initial Exposure but with sharply different orientation.

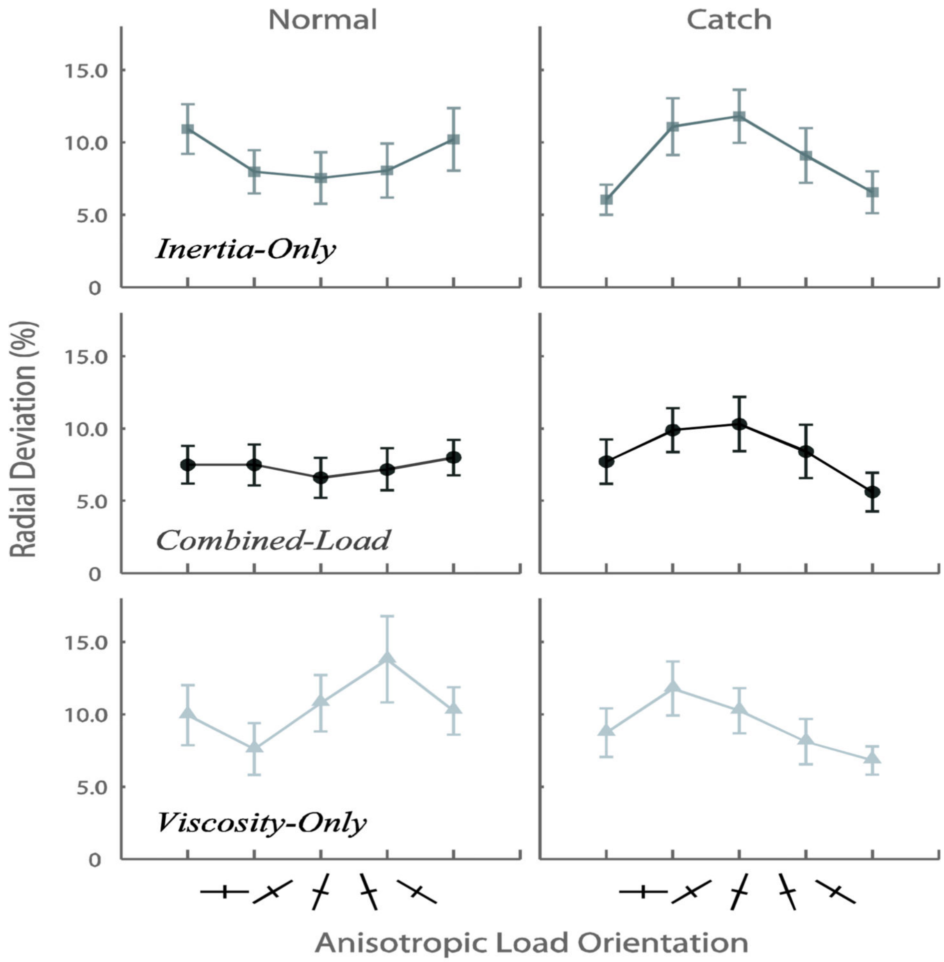

Fig. 2.

Radial deviation trends for normal (left) and catch (right) trials reveal differences in sensitivity to load axis (5 conditions, indicated by cross) for each subject group (by rows). The Combined-Load group achieves the lowest error and lowest sensitivity in normal trials and exhibits comparable behavior to Inertia-Only in catch trials. The Viscosity-Only group exhibits larger error overall in normal conditions and lowest error in catch trials, suggesting reduced feedforward mass compensation. Error-bars indicate 95% confidence intervals across subjects and trials (first two trials of normal conditions per load, all two catch trial per load).

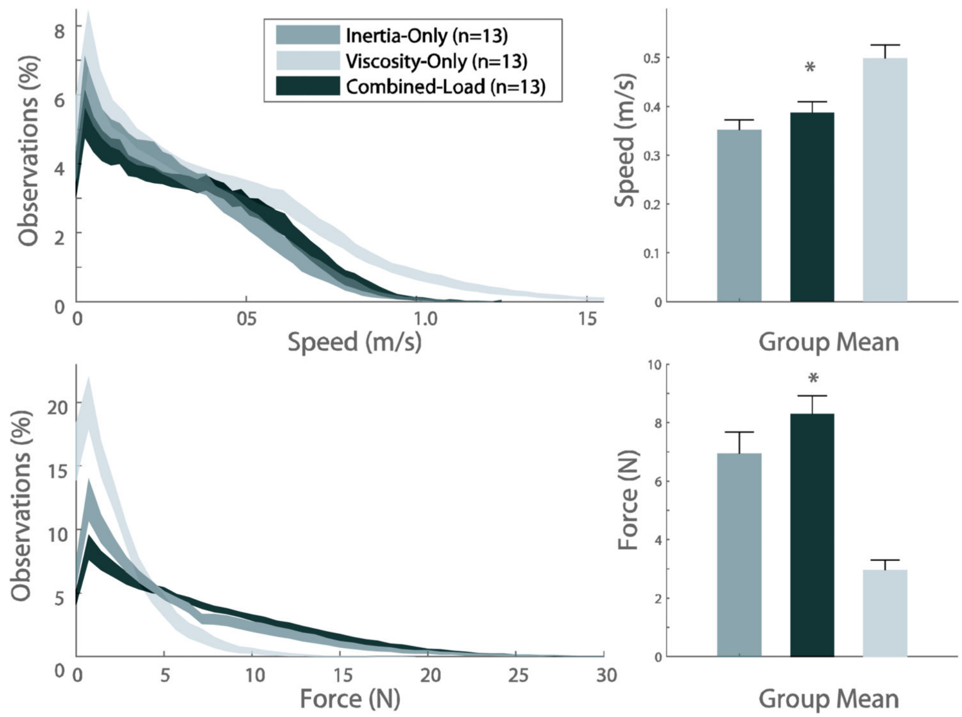

Fig. 3.

(A) During free exploration prior to task performance, the Combined-Load (inertia and negative viscosity) training group exhibited modest differences indicating broader distributions (average of all subjects and load conditions) of speed and computed endpoint force (along the axis of the inertial load) compared to Inertia-Only exploration. (B) Quantitative comparisons, however, confirm that the Combined-Load training group exhibited greater increase in average speed (12.0%) and computed end-point force (22.9%) compared to Inertia-Only exploration. The Combined-Load training group exhibited lower average speed compared to the Viscosity-Only group (18.8%), but the experienced higher average forces (179.0%). Error bars represent 95% CI across all trials.