Adaptation to Visuomotor Rotation in Isometric Reaching is Similar to Movement Adaptation

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***Abstract*—Isometric reaching, in which the arm remains stationary and the user controls a virtual cursor via force input, is a motor task that has not been thoroughly compared to real reaching. In this study, we ask if isometric adaptation to a kinematic perturbation is similar to adaptation in movement, and if the type of isometric mapping (position or velocity control) influences learning. Healthy subjects made real and virtual reaches with the arm in plane. In some trials, the cursor was rotated counter clockwise by 45° to perturb the kinematic mapping. To assess adaptation, the angular error of cursor movement at 150 ms from movement onset was measured for each reach; error was averaged across subjects and a two-state learning mode was fit to error data. For movement and isometric groups, average angular error peaked at perturbation onset, reduced over 200 reaches, and reversed direction when the perturbation was removed. We show that subjects are able to adapt to a visuomotor rotation in both position- and velocity-based cursor control, and that the time course of adaptation resembles that of movement adaptation. Training of virtual reaching using force/torque input could be particularly applicable for stroke patients with significant movement deficits, who could benefit from intensive treatments using simple, cost-effective devices.**

I. Introduction

A. Motivation

When individuals suffer motor injuries to the upper limb, due to stroke or demyelinating disease, treatment may include rehabilitation to rebuild neural pathways and restore motor function. Currently, movement therapy includes labor-intensive treatment by a therapist, or robot-aided therapy, which requires expensive devices that are limited to laboratory or clinical settings [1]. Since training quantity, intensity, and task-specificity are important treatment parameters, an ideal rehabilitation solution is one that is automated using simple, cost-effective, and take-home devices. Isometric training, in which the arm is stationary and user-applied force/torque is used to control a cursor in a virtual environment, is a potential solution for diagnosis [2] and the retraining [3] of reach in motor-impaired individuals. Isometric training requires no minimum level of ability, improves muscle strength, and can be tailored to patient performance [4]. Further, isometric devices are mechanically simple to construct and could be integrated into both home and clinical settings. Despite these advantages, isometric control is unlike real movement in that proprioceptive feedback is lost. There may also be dissimilarity in muscle activation, which in real movement may change based on the arm's location in different areas of the workspace.

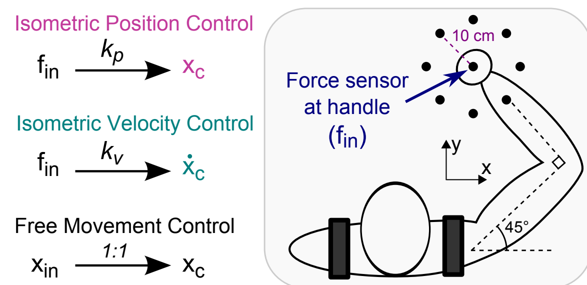

Fig. 1. Subjects are positioned with arm at shoulder height with 45° and 90° flexion at shoulder and elbow. Real and virtual reaches are made to 8 targets arranged in a circular pattern, with 10 cm radius. The movement of a virtual cursor is controlled using either static force (f_{in}) or displacement input (x_{in}) of the manipulandum handle. In movement, handle position corresponds directly to cursor position (x_c), whereas in the isometric case, force applied to a sensor maps to either cursor position (x_c) or velocity ($\dot{x}_c$).

In this study, we take an initial step towards understanding the relationship between isometric reaches and real reaches. Participants performed a target-acquisition task in movement and isometric conditions with a visual rotation of the visible cursor applied for some trials. By applying this perturbation and assessing the initial angular error of the cursor trajectory from a straight path, we aimed to evaluate adaptation and assess similarity between adaptation in isometric and free movement conditions.

While free movement of the arm affords a direct mapping between the Cartesian position of the hand to that of the cursor, in isometric control we explore two control strategies: position control, where input force maps to cursor position, and velocity control, where input force maps to cursor velocity (Fig. 1). We aimed to determine whether the type of mapping (position or velocity) influences adaptation. We show that adaptation in the isometric case is similar to movement and that position and velocity control mappings are comparable. The results of this preliminary study provide the foundation for continued exploration of isometric tasks in rehabilitation.

B. Related Work

User adaptation to dynamic and kinematic perturbations of the arm have been extensively studied. When arm dynamics are perturbed by applying a mechanical force field to the hand, typical straight-line hand paths are replaced by hooked trajectories. Shadmehr and Mussa-Ivaldi [5] hypothesized that the mechanical perturbation causes the motor system to con-

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tinuously update its internal model of the arm, which causes hand paths to gradually straighten with repeated exposure to the perturbation. Removal of the perturbation results in an aftereffect, characterized by a deviation of the path in the opposite direction. When cursor kinematics are altered through the application of a visuomotor rotation or visual scaling, a similar adaptation pattern is observed [6]. While both kinematic and dynamic internal models affect arm movement, these were found to adapt independently, with visual feedback primarily affecting the kinematic model and force and torque information affecting the dynamic model [7].

While isometric force trajectories have been studied [8], isometric adaptation to kinematics has only been studied in joint space [9]–[11]. In comparison to this work, we study adaptation to a visuomotor rotation with the arm in a position relevant to planar reaching. We use force applied by the user at the hand to control a cursor in Cartesian space, appropriate for rehabilitating point-to-point reaching movements, and consider both position- and velocity- based mappings.

Studies of human-machine interfaces have explored how the control mapping influences user performance in spatial manipulation tasks. Zhai and Milgrim [12] report that in a 6-DOF virtual manipulation task, an isometric (force) input with rate control (as opposed to position control) led to improved performance in a positioning task. Compared to movement-based position control, isometric rate control was found to be harder to learn, but comparable in performance over time. Rate and position control showed comparable error in a 1-DOF finger targeting task over a transition from movement to isometric conditions [13]. Based on previous results, we hypothesize that for our isometric reaching task: (1) there will be adaptation to the visuomotor rotation, and (2) the adaptation may be similar between movement and isometric conditions, with differences between the isometric mappings.

II. Materials and Methods

In this study we aimed to compare how healthy participants adapt to a kinematic perturbation during real and virtual planar reaches. Participants performed a center-out reaching task involving movement of a cursor to 8 circular targets located at a distance of 10 cm from the center of the workspace (Fig. 1). Reaches were made by either physical movement or application of force to the handle of a robotic manipulandum.

A. Experiment Workstation

A 2-DOF planar manipulandum prototype, depicted in Fig. 2A, was designed and built for this study, similar to robots used in other motor control studies, e.g. [14]. In addition to free movement, the device can also be used for isometric tasks by mechanically locking the links. In movement mode, two Maxon RE 40 series DC brushed motors can apply forces to the handle of the robot through cable transmissions. These forces were used only between movement trials to passively return the hand of the participant to center. The device has a 0.9 m radius workspace with angular sensing error of 0.72°.

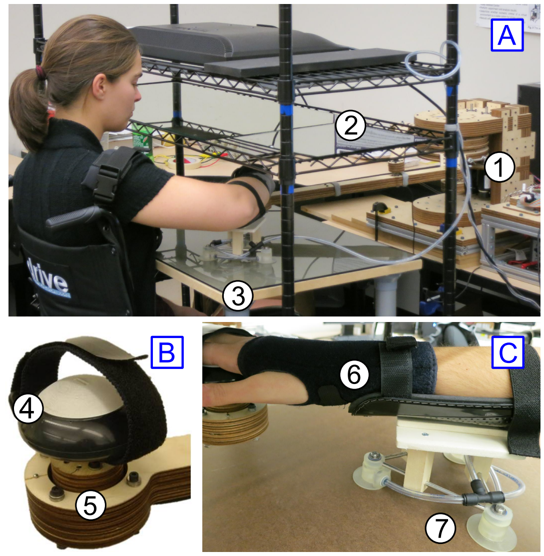

Fig. 2. A. Users are seated in front of the device workstation where they interact with the manipulandum (1) and receive visual feedback through a mirrored projection set-up (2). B. The user's hand grasps the rotating handle (4), and applied forces are measured by a 6-DOF force sensor embedded in the handle (5). C. Wrist rotation is constrained using a brace (6), and the arm is supported by a triangular air bearing (7) that slides atop a glass table (3).

The user's hand is placed on a free-rotating rubber handle and secured with a comfortable strap (Fig. 2B). In isometric mode, the user applies force to the handle, instrumented with an ATI Mini-45 force-torque sensor with 0.125 N resolution. Force is recorded at 400 Hz and filtered using a second-order Butterworth filter with 2.75 Hz cutoff frequency. The x-y force is mapped to the movement of a visual cursor displayed on a screen, and a force deadband of ± 0.2 N was applied to reduce the effect of noise on cursor movement. Due to mechanical slippage, there was maximum error of 0.2° in the measured force direction during isometric trials.

Users are seated in a transport chair in front of an adjustable workstation; the chair is lockable and features a shoulder harness to limit excessive trunk movement during reaching. The arm of the subject is positioned in plane with the shoulder, and supported by an air bearing (Fig. 2C). The air bearing design, modeled after [15], features a triangular base with 3 air jets localized at the corners, and an arm support with Velcro straps. The arm moves with minimal friction over an adjustable glass-top table, and the wrist is constrained with a brace.

Graphics are projected from a monitor onto a horizontal mirror placed above the arm. The positioning of the mirror at approximately equal distance from the monitor and hand gives a perception of depth and colocation between arm and cursor movement planes. The arm remains occluded from the user throughout the experiment. The display shows the cursor, target locations, instructions, and feedback of cursor speed.

B. Force Calibration and Control Mappings

In movement trials, the position of the robot handle directly mapped to the cursor position; the cursor movement was spatially aligned and equally scaled. In contrast, in the isometric

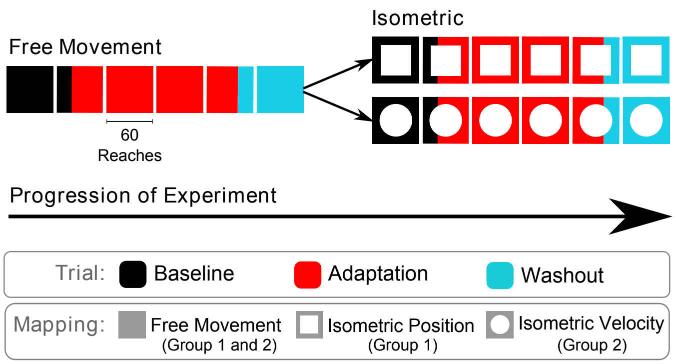

Fig. 3. Progression of experiment trials. Each block represents 60 reaches, and color indicates baseline, adaptation, or washout segments. All subjects complete 360 Free Movement trials, followed by 360 reaches in either isometric position (Group 1) or isometric velocity (Group 2) conditions. Space between blocks represents break periods.

modes, the force applied on the static handle was mapped to cursor movement.

Prior to the experiment, we calibrated force sensor inputs by asking participants to execute maximal force exertions in four directions (towards-away and left-right). For each direction, subjects applied a maximal force over a 3-second period, and a maximum force was found for each direction. The minimum of these forces was selected as the maximal force, f_{max}, and was used to specify the isometric control mappings.

In position control, f_{max} for each subject was mapped to the control gain k_{p} via constant c_{p}, experimentally selected to be 0.28 m to produce smooth hand paths and responsive control.

$$\vec{x}_{\text{cursor}} = k_{\text{p}}\vec{f}_{\text{in}}, \quad k_{\text{p}} = c_{\text{p}}/f_{\text{max}}, \tag{1}$$

where, $\vec{x}_{\text{cursor}} = (x, y)^T$ and $\vec{f}_{\text{in}} = (fx_{\text{in}}, fy_{\text{in}})^T$. Similarly, for velocity control, c_{v} was experimentally selected as 2 m/s and f_{in} was mapped to the cursor velocity:

$$\dot{\vec{x}}_{\text{cursor}} = k_{\text{v}}\vec{f}_{\text{in}}, \quad k_{\text{v}} = c_{\text{v}}/f_{\text{max}}, \tag{2}$$

where, $\dot{\vec{x}}_{\text{cursor}} = (\dot{x}, \dot{y})^T$. Numerical integration of velocity yielded the cursor position that was visually displayed. Our selected control gains created input forces relevant to forces produced during free movements. We also tested acceleration-based control in pilot study, but found that it was too difficult for participants to learn.

C. Participants

Ten healthy, right-handed volunteers participated in the study. The participants (6 male and 4 female) were between ages 21 and 32. The protocol was approved by the Stanford Institutional Review Board, and informed consent was obtained.

D. Experiment Protocol

We tested adaptation to a visuomotor rotation in free movement (FM), as well as adaptation in two isometric environments: isometric position (IP) and isometric velocity (IV). To eliminate bias from ordered exposure to the control environments, each subject performed the experiment in FM and *one* of the two isometric modes. Group 1 was tested with the IP mapping and Group 2 was tested with the IV mapping.

For all conditions, the arm was positioned in plane with the shoulder, with shoulder at 45° and elbow at 90° flexion relative to the upper arm. Participants were asked to perform center-out reaching movements by controlling a circular cursor of radius 6 mm to circular targets of 9 mm radius. Participants were instructed to move the cursor from the center of the workspace to the given target with the goal of making fast and accurate movements. Each trial was completed when the cursor was fully within the visual target for 0.5 s or the length of time from the start of movement exceeded 4 s. When the target was successfully acquired, feedback of the maximum cursor speed was displayed using colored circles. The speed was calculated using numerical differentiation of cursor position and was filtered using a second order discrete-time filter, described by a linear difference equation and cut-off frequency of 3.25 Hz. If $v_{\text{max}} < 0.35$ m/s, a blue circle indicated the movement was too slow, if $v_{\text{max}} > 0.6$ m/s, a yellow circle indicated movement was too fast, and if v_{max} was bounded by these two values, a green circle indicated that movement speed was acceptable.

Fig. 3 shows the time course of the experiment and the grouping of trials into Baseline (80 reaches), Adaptation (200), and Washout (80). Baseline trials characterize behavior prior to visuomotor rotation exposure. During all adaptation phases (movement and isometric), the subject experienced a 45° counter-clockwise (CCW) rotation of the cursor on the display. Cursor rotation was removed in the washout phase. In the isometric environments, the cursor automatically returned to center after each trial. In FM, the device returned the subject's hand back to center after each trial, maintaining consistent exposure to the visual rotation across all conditions. Breaks of at least 30 seconds were given after every 60 reaches.

E. Data Analysis

For all cursor trajectories, we filtered velocity data using a 3rd order Butterworth filter with 6 Hz cutoff frequency. We defined the onset of movement when the cursor's velocity reached 5% of the within-trial maximum, searching backwards from the maximum. Movement trajectories were inspected manually, and movement onset was corrected, as needed. Excessively slow reaches in which the maximum velocity of the cursor was less then 0.2 m/s were excluded; this insured that the part of the trajectory we analyzed had not been significantly influenced by within-reach visual feedback. Trials that "timed out" were not excluded as long as the endpoint of the trajectory was in the direction of the target.

To assess adaptation, we measured the angular error between the cursor position at 150 ms from movement onset and the straight-line path to the target. Positive error indicated a CCW rotation of the cursor. Errors larger than ±75° were identified as outliers and discarded before averaging. The error for each trial was averaged across all subjects in each group (n=10 in free movement and n=5 in isometric), and the 95% confidence interval of the mean error was computed from the t-distribution.

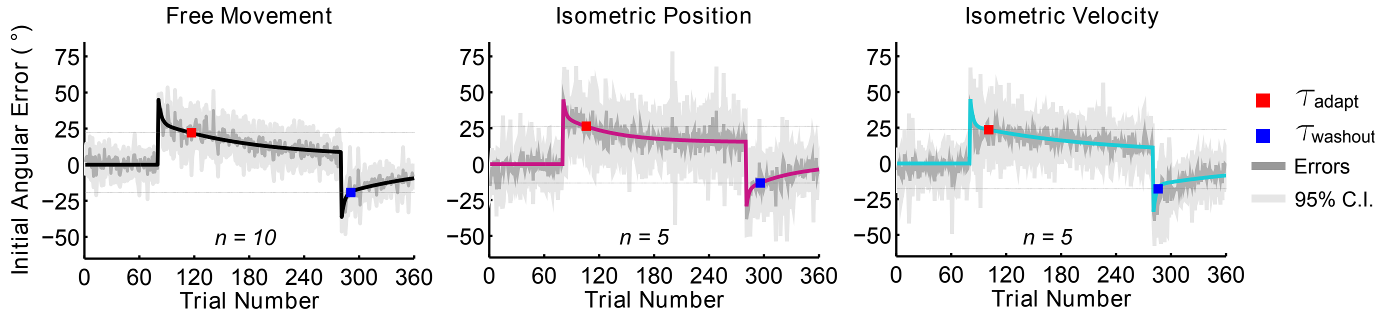

Fig. 4. Average angular error (dark gray) is compared across free movement (FM), isometric position (IP), and isometric velocity (IV) conditions. Errors for each condition are fit with a two-state learning model. Shaded areas (light gray) show the 95% confidence interval about the mean error for each trial. Red and blue squares on each curve show the calculated time constants for adaptation and washout, respectively. For all conditions, angular error peaks at the onset of of the visual perturbation (Trial 81), decreases exponentially over 200 trials, and changes direction when the perturbation is removed (Trial 281). Adaptation is similar in rate and extent across FM, IP, and IV conditions.

To compare adaptation across movement and isometric conditions, we fit a two-state learning model [16] to the average error data. The model primarily describes trial-to-trial adaptation using two states, and captures fast and slow learning processes in two sets of learning rate and retention rate parameters. Although our experiment includes movements to multiple targets, which may introduce unmodeled generalization effects, we justify use of the model only as a tool to obtain a robust estimation of learning time constants. Compared to a single-state model, the two-state mode better fit the data and has been shown to account for more learning effects related to visuomotor adaptation [17].

Before fitting each data set, we computed the average error for the last 8 trials in baseline and offset all subsequent error measurements. As an additional metric, we calculated two time constants on the model fit, τ_{adapt} and τ_{washout}, representing the average number of trials to reach 63.2% of the change in error for the adaptation and washout periods, respectively. A bootstrap algorithm was implemented with 200 iterations to generate 95% confidence intervals about mean τ values.

III. Results

Fig. 5 shows plots of the cursor paths for typical subjects A and B over a sequence of experiment stages and depicts the motor system's adaptation to the visual cursor rotation. In FM, baseline movements are characterized by straight-line paths to the targets. Once the visual rotation is introduced, paths are sharply hooked with angular deviation comparable to the magnitude of perturbation. After training with the rotation for 200 movements, the reaches again converge toward straight paths as the subject gradually adapts. When the perturbation is suddenly removed, there is evidence of an aftereffect: the initial washout movements are biased in the opposite direction. Interestingly, we see similar path patterns in both the IP case for the same subject and the IV case for Subject B. Compared to movement, the isometric condition includes a greater portion of the trajectory spent stabilizing the cursor at the target in IP and more prevalent overshoot in IV.

Fig. 4 shows the average initial angular error for all trials for FM, IP, and IV conditions. The error points, connected by the dark-gray line, appear to have less variability in FM due to the inclusion of data from all 10 subjects, compared to 5 subjects in each of the isometric conditions. The learning models that were fit to the data (solid curves) are similar across all conditions and highlight the initial 45° cursor error due to the perturbation. Finally, the red and blue markers on the plot that represent τ_{adapt} and τ_{washout} visually indicate the relative rates of learning and unlearning.

To further assess adaptation and aftereffects quantitatively, we calculated the average errors in 8 first and last trials from the adaptation phase, and in 8 first trials from the washout phase. These are depicted for the different cursor control conditions in Fig. 6A. In all conditions, we see a large initial error that is reduced with adaptation, and nearly equal errors in the opposite direction in washout. Overlapping

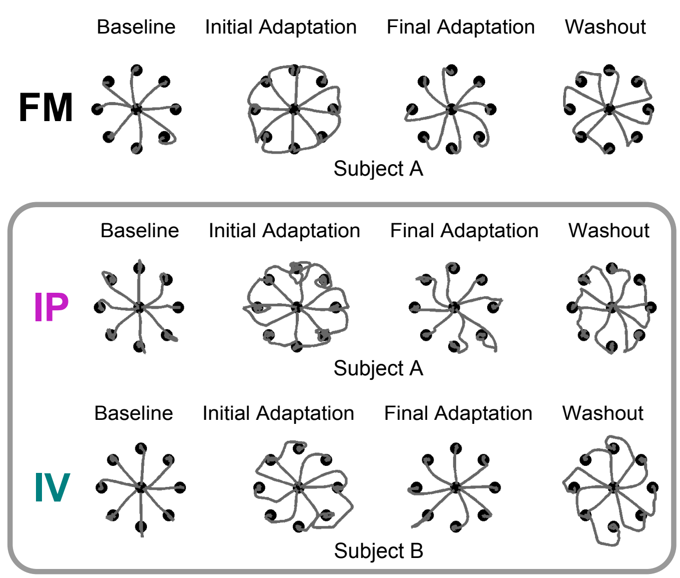

Fig. 5. Hand paths in free movement (FM), isometric position (IP), and isometric velocity (IV) cases are shown for the last 8 reaches of the baseline, first/last 8 reaches of adaptation, and first 8 reaches of washout. Paths during the baseline and final adaptation stages are relatively straight, whereas large CCW/CW cursor deviations are observed in early adaptation/washout.

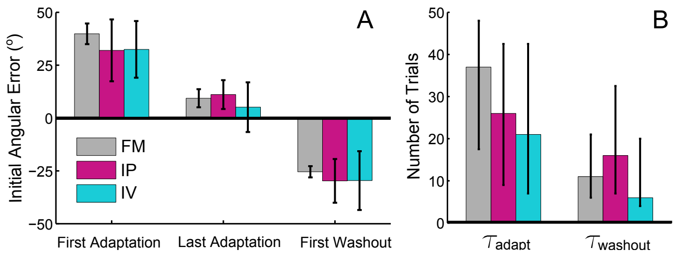

Fig. 6. A. Initial angular error for the first/last 8 adaptation trials and first 8 washout trials are shown for free movement (FM), isometric position (IP), and isometric velocity (IV) conditions. Angles are similar across all conditions and are equal and opposite for initial adaptation and washout. B. Average time constants for learning and unlearning are statistically equivalent, with slightly faster unlearning. Error bars indicate the 95% confidence interval of the mean, calculated using the t-distribution in (A) and using a bootstrap method in (B).

confidence intervals show that learning is similar in movement and isometric environments, with no significant difference between the isometric position and velocity mapping. In Fig. 6B, the average values for τ_{washout} are generally less than those for τ_{adapt}, indicative of faster unlearning. The reported averages for τ_{adapt} in the isometric cases were less than in movement, though not significantly. Further, there was no significant difference in the models' learning and retention rate parameters across movement and isometric conditions (results not shown). In future studies we will examine whether these results are due to small sample size, or whether there is no genuine difference between the adaptation rates in the different groups.

IV. Discussion

We showed that the motor system adapts to visuomotor rotations not only in movement tasks, but also in virtual, isometric reaching using both position and velocity mappings.

In the movement case, errors in the extent and direction of reach drive the motor system to update the internal kinematic model, which in turn plans the correct motor command to be executed via the arm's actuators. While adaptation occurs primarily in the kinematic model, an accurate internal dynamic model is also required for the correct estimation of the kinematic parameters and motor commands [6]. In comparison, in the isometric case, the actual dynamics of the arm are removed. To complete the isometric reaches, only a single estimate of the arm position in the static configuration and the virtual mapping from force to cursor movement are needed.

In our study, adaptation in both movement and isometric conditions relied primarily on updating the kinematic model, driven by continuous visual feedback of the cursor [7]. Since the visual feedback in both movement and isometric cases is equivalent, we see comparable adaptation and evidence that the lost proprioception in the isometric task did not affect learning of the kinematic model. This result is consistent with a previous study [18] in which two deafferented patients were found to adapt to a 30° rotation in a reaching task at the same rate and extent compared to healthy subjects.

While there is a rationale for why adaptation and aftereffects are similar in the movement and virtual reaching tasks, we acknowledge that all isometric trials in this study were preceded by movement trials, where subjects were exposed to the same 45° cursor rotation. To test if adaptation would occur regardless of the experiment order, we performed a small supplementary experiment (data not shown) in which two subjects completed the reaches in the IP/IV task prior to the movement. We saw similar evidence of adaptation; however, because the reversed order experiment was performed with a single subject for each isometric mapping, we cannot generally conclude that order does not have an effect. Though learning in the movement and isometric reaches was statistically equivalent, faster initial learning rates in isometric conditions may possibly be explained through savings from movement, where learning of the rotation in FM may have increased the rate in which the rotation was re-learned in IP and IV. Savings and additional effects such as anterograde interference, where the rate of subsequent learning of an equal but opposite perturbation is increased, is demonstrated in other studies [16]. Potential effects of savings and order within this experiment should be identified by repeating the experiment with two additional subject groups that complete the isometric reaching task prior to movement. Further, differences in the average learning rates between isometric mappings may reflect differences in the generalization of adaptation to different targets.

In spite of no observable difference in adaptation between groups 1 and 2 that learned the IP and IV mappings, respectively, participants reported a varying amount of difficulty in task performance for each case. Since the mapping between force and cursor movement was scaled by the maximum force determined by the force calibration, the large variability in F_{max} (ranging from 14.42 N to 57.52 N, with average F_{max} = 39.14 N) resulted in a range of levels of cursor responsiveness. Further, it was difficult to select an optimal constant for mapping force to velocity. Participants often could not make sufficiently accurate movements to the targets while maintaining the objective speed. Feedback that cursor movement was "slow" created frustration for several subjects, whereas one reported that the velocity mapping felt very easy to control. On the other hand, the isometric position mapping allowed for good cursor speed, but was harder to precisely control at the target due to the need to stabilize a large input force to maintain a target. These observations highlight the importance of selections of mapping parameters, and may suggest relaxing task difficulty via larger target sizes or a longer allowable time to complete the task.

Despite different user opinion, the rate of adaptation was the same across conditions. This is consistent with the hypothesis of separate control of reaching extent and direction [8]; though the extent of cursor movement varied between mappings, the adaptation in reaching direction was similar in all isometric cases. Yet, there may be subtle differences between the two mappings, which might not be detected by this study due to small sample size. The robustness of this study could be improved by testing larger numbers of subjects in the different testing groups, by collecting equal numbers of subjects to perform the isometric and movement adaptations in reverse order, and possibly, by extending the number of trials within each adaptation protocol. This would further isolate the effects of learning transfer across conditions. For all participants, learning did not washout within the given 80 reaches.

Visuomotor transformations are applicable to rehabilitation [19]. Given that visual feedback, alone, can be used to update the internal model of external arm dynamics in force-field adaptation [20], we hypothesize that learning of visual cues in an isometric environment (in the absence of proprioception) may transfer to natural movement. However, compared to healthy individuals, patients would require different system gains and also have impaired timing of joint torques [21].

V. Conclusion

In this study we showed that adaptation to a 45° CCW visuomotor rotation during virtual isometric reaching is similar to adaptation in actual reaching. In each case, the introduction of the perturbation caused a large angular error in the initial cursor path, evident in hooked trajectories. Over a period of 200 trials, subjects adapted to the rotation and reaching paths returned to straight. Removal of the perturbation caused errors in the opposite direction, which similarly washed out over time. Analysis of the two-state learning models fit to the movement error indicate not only that people adapt in the isometric case, but also that learning is comparable in rate and extent to that in actual movement and is independent of the isometric mapping.

Beyond establishing baseline evidence for isometric adaptation, the next step in this line of work is exploring how learning generalizes to different directions in the workspace and further how it generalizes to movement tasks. To date, isometric training has been used in stroke patients to correct abnormal synergies and promote proper elbow extension and shoulder flexion torques [3], though transfer of learning to actual movement has not been established. In future work, we plan to identify potential differences in how learning may be influenced by position and velocity isometric mappings, in addition to acceleration mappings that include more complex and realistic inertial and damping parameters.

Isometric training represents an exciting avenue for new rehabilitation therapies, as isometric devices are simple, cost-effective, and highly transportable. Training of virtual movements using force/torque input may engage individuals of a wide range of abilities and ultimately broaden the impact of rehabilitation for individuals with reaching deficits.

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References

[1] W. Harwin, J. Patton, and V. Edgerton, “Challenges and opportunities for robot-mediated neurorehabilitation,” *Proceedings of the IEEE*, vol. 94, pp. 1717–1726, 2006.

[2] M. Casadio, V. Sanguineti, G. Brichetto, P. Morasso, C. Solaro, C. Mariotti, and S. Di Donato, “Control of position and isometric force in patients with Friedrich ataxia,” *5th National Congress of SIAMOC*, pp. 113–136, 2004.

[3] M. D. Ellis, B. G. Holubar, R. F. Beer, A. M. Acosta, and J. P. Dewald, “Modifiability of abnormal isometric elbow and shoulder joint torque coupling after stroke.” *Muscle & Nerve*, vol. 32, pp. 170–178, 2005.

[4] J. P. A. Dewald, V. Sheshadri, M. L. Dawson, and R. F. Beer, “Upper-limb discoordination in hemiparetic stroke: Implications for neurorehabilitation.” *Topics in Stroke Rehabilitation*, vol. 8, pp. 1–12, 2001.

[5] R. Shadmehr and F. A. Mussa-Ivaldi, “Adaptive task of dynamics during learning of a motor,” *Journal of Neurosci.*, vol. 74, pp. 3208–3224, 1994.

[6] J. W. Krakauer, Z. M. Pine, M.-F. Ghilardi, and C. Ghez, “Learning of visuomotor transformations for vectorial planning of reaching trajectories.” *The Journal of Neuroscience*, vol. 20, pp. 8916–8924, 2000.

[7] J. W. Krakauer, M. F. Ghilardi, and C. Ghez, “Independent learning of internal models for kinematic and dynamic control of reaching.” *Nature Neuroscience*, vol. 2, pp. 1026–1031, 1999.

[8] C. Ghez, M. Favilla, M. F. Ghilardi, J. Gordon, R. Bermejo, and S. Pullman, “Discrete and continuous planning of hand movements and isometric force trajectories.” *Experimental Brain Research*, vol. 115, pp. 217–233, 1997.

[9] A. de Rugy, M. R. Hinder, D. G. Woolley, and R. G. Carson, “The synergistic organization of muscle recruitment constrains visuomotor adaptation.” *Journal of Neurophysiology*, vol. 101, pp. 2263–2269, 2009.

[10] D. G. Woolley, J. R. Tresilian, R. G. Carson, and S. Riek, “Dual adaptation to two opposing visuomotor rotations when each is associated with different regions of workspace.” *Experimental Brain Research*, vol. 179, pp. 155–165, 2007.

[11] D. G. Woolley, A. de Rugy, R. G. Carson, and S. Riek, “Visual target separation determines the extent of generalization between opposing visuomotor rotations.” *Experimental Brain Research*, vol. 212, pp. 213–224, 2011.

[12] S. Zhai and P. Milgram, “Human performance evaluation of manipulation schemes in virtual environments,” *Proceedings of IEEE Virtual Reality Annual International Symposium*, pp. 155–161, 1993.

[13] T. L. Gibo, M. F. Rotella, A. J. Bastian, and A. M. Okamura, “Gradual anisometric-isometric transition for human-machine interfaces.” *33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4507–4510, 2011.

[14] H. I. Krebs, M. Ferraro, S. P. Buerger, M. J. Newbery, A. Makiyama, M. Sandmann, D. Lynch, B. T. Volpe, and N. Hogan, “Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus.” *Journal of Neuroengineering and Rehabilitation*, vol. 1, pp. 1–15, 2004.

[15] I. S. Howard, J. N. Ingram, and D. M. Wolpert, “A modular planar robotic manipulandum with end-point torque control.” *Journal of Neuroscience*, vol. 181, pp. 199–211, 2009.

[16] M. A. Smith, A. Ghazizadeh, and R. Shadmehr, “Interacting adaptive processes with different timescales underlie short-term motor learning.” *PLoS biology*, vol. 4, pp. 1035–1043, 2006.

[17] J. Y. Lee and N. Schweighofer, “Dual adaptation supports a parallel architecture of motor memory.” *Journal of Neuroscience*, vol. 29, pp. 10 396–10 404, 2009.

[18] P. M. Bernier, R. Chua, C. Bard, and I. M. Franks, “Updating of an internal model without proprioception: a deafferentation study.” *NeuroReport*, vol. 17, pp. 1421–1425, 2006.

[19] B. R. Brewer, R. Klatzky, and Y. Matsuoka, “Visual feedback distortion in a robotic environment for hand rehabilitation.” *Brain Research Bulletin*, vol. 75, pp. 804–813, 2008.

[20] A. Melendez-Calderon, L. Masia, R. Gassert, G. Sandini, and E. Burdet, “Force field adaptation can be learned using vision in the absence of proprioceptive error.” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 9, pp. 298–306, 2011.

[21] P. H. McCrea, J. J. Eng, and A. J. Hodgson, “Time and magnitude of torque generation is imparied in both arms following stroke.” *Muscle & Nerve*, vol. 28, pp. 46–53, 2003.