

# Force Field Learning in Joint Space with a 7-DOF Exoskeleton

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Previous studies have used force field experiments to investigate the principles and representations of planning, execution, and learning of arm movements in the CNS. When making reaching movements to a visual target in the presence of a force field, subjects initially show distorted endpoint trajectories, which eventually return to normal after repeated trials. However, aftereffects appear (opposite to initial distortions) when the force field is suddenly removed, suggesting that the CNS adapts to the field by learning an internal model that predicts, and thus cancels, the perturbing forces.

So far, however, experiments have been constrained to planar two joint movements, i.e., non-redundant degrees-of-freedom (DOF) movements, due to the two DOF manipulanda that were developed for this experimental paradigm. A new experimental setup permits us to explore a novel variety of issues within the force field paradigm, including full 3-D movements involving the major 7 DOF of the human arm. We incorporate a 7 DOF robot exoskeleton as a manipulandum, and minimize weight and inertia through gravity, Coriolis, and inertia compensation, such that subjects' arm movements are largely unaffected by the exoskeleton in the absence of a force field. Individual fields can be applied to any or all major 7 joints of the human arm, and because of the inherent redundancy in 7 DOFs, we can also examine effects of the force fields in the null space of a movement.

Our first study investigates a joint space force field where the shoulder velocity drives a disturbing force in the elbow joint. Results demonstrate that subjects learn to compensate for the force field within about 100 trials, and, from the strong presence of aftereffects when removing the force field in some randomized catch trials, that an internal model of the force field was formed. Interestingly, while after learning, endpoint trajectories return to baseline, joint space trajectories remained changed in response to the field, indicating that, besides learning a model of the force field, the CNS also chose to exploit the null space to minimize the effects of the force field on the realization of the endpoint trajectory plan. We discuss these results in the light of current theories of inverse kinematics and optimal control.