Force Synergies Within and Across the Two Hands in Bimanual Skill Acquisition

Caroline Savio*, Kunpeng Yao*, Aude Billard

Learning Algorithms and Systems Laboratory, School of Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Bimanual fine-manipulation tasks demand the collaboration of both hands and rely on the coordinated forces applied by fingers from both hands. Despite the abundant degrees of freedom (DoFs) of our hands, humans distribute the roles across hands and apply balanced forces among fingers nearly effortlessly. Multiple fingers often coordinately generate the desired force, namely through force synergies. The concept of force synergy explains well the force profiles in grasping and unimanual manipulation tasks. In this study, we sought to evaluate whether and how force synergies evolve as subjects improve fine bimanual skills.

We conducted a longitudinal study by following watch-making apprentices in the first two years of their study. Skills were recorded in multiple sessions, every 6 months. We focused on a typical bimanual fine-manipulation - the assembly of a watch plate. Subject uses one hand to control a pair of tweezers, to pinch and insert the plate into a slot; and the other hand to hold a peg-wood to stabilize the watch face by pressing. We analysed the task performance of 6 right-handed subjects (aged 16-40, 21 /- 8.56), divided in two groups - apprentice and expert, with 3 subjects in each group. Apprentices took part in 3 consecutive recording sessions, 6 months apart, to follow their skill progresses. The three experts took part in a single recording session. In each session, subjects were instructed to perform 8 repetitions of the task as fast and as accurately as possible. A high-resolution camera mounted on the forefront of the subject captured the hands' postures. Soft wearable finger sensors fixed on multiple finger digits of the subject recorded the applied pressure.

Comparative analysis of hand postures showed small intra-subject variations of finger placement but no significant differences across experts and apprentices. A temporal analysis of finger forces against performance level reveals that, as subjects gain more experience, they use fewer fingers to apply forces, and with smaller amplitude. This prevents excessive energy consumption, an economy of skilled movements. A principal component analysis was applied to uncover force synergies both within and between hands. We find that as subjects gained more expertise, synergies across the two hands reveal a clear division of task. Task-related activities were concentrated in the dominant hand, while the variance in forces applied by the non-dominant hand largely decreased. For within-hand synergies, novices mainly employ synergies that co-activate multiple finger digits. In contrast, experts tended to use simpler synergies for both hands, using primarily the thumb and index finger. Experts seem to revert to common used synergies, albeit directed to new tool usage. This strategy helps to focus efforts on achieving highly precise control and avoids learning new synergies that require inhibiting existing fingers' bio-mechanical couplings.

* Authors contributed to the work equally.