

Control of Prehension

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We studied the coordinated action of fingers during static tasks involving exertion of force and torque on a hand-held object. Normal and shear forces were measured from the individual digits with 6-component force sensors. We report the results of two experiments.

Experiment 1. Finger forces and antagonist finger activity. Subjects were asked to keep a handle with an attachment that allowed for independent change of the suspended load (0.5-2.0 kg) and external torque (0.375-1.5 Nm) in a vertical position. Antagonist finger moments acting opposite to the intended direction of the total moment were always observed. At low torques, the antagonist moments were as high as 40-60% of the agonist moments. A *three-zone model* of coordinated finger action is suggested. In the first zone of load/torque combinations, activation of antagonist fingers, i.e. fingers that generate antagonist moments, is necessary to prevent slipping. In the second zone, the activity of agonist fingers is sufficient for preventing slips. In the third zone, the performer has freedom to choose between either activating the antagonist fingers or redistributing activities amongst the agonist fingers. Optimization was performed using as criteria the cubic norms of (a) finger forces, (b) finger forces normalized with respect to the maximal forces measured in single-finger tasks, (c) finger forces normalized with respect to the maximal forces measured in a four-finger task and (d) finger forces normalized with respect to the maximal moments that can be generated by the fingers. All four criteria failed to predict antagonist finger moments when these moments were not imposed by the task mechanics. Reconstruction of neural commands: The vector of neural commands $[c]$ was reconstructed from the equation $[c] = [W]^{-1}[F]$, where $[W]$ is the finger interconnection weight matrix adjusted from Zatsiorsky *et al.* (1998) and $[F]$ is the vector of finger forces. The neural commands ranged from zero (no voluntary force production) to one (maximal voluntary contraction). The individual finger forces were decomposed into forces due to 'direct' commands and forces induced by enslaving effects. Optimization of the neural commands resulted in the best correspondence between actual and predicted finger forces. The antagonist moments are, at least in part, due to enslaving effects: strong commands to agonist fingers also activated antagonist fingers.

Experiment 2. Prehension synergies: Trial-to trial variability and hierarchical organization of stable performance. Subjects (n=6) stabilized a handle with an attachment that allowed for change of external torque. Each subject performed 25 trials at each of the five torques -1.0 Nm, -0.5 Nm, 0 Nm, 0.5 Nm and 1.0 Nm while the total load was always 14.9 N. Forces and moments exerted by the digit tips on the object were recorded. In spite of the variability of individual forces and points of their application the stable performance was achieved by the fine-tuning among force components (prehension synergies). Some of the observed phenomena (e.g. a V-like relationship between the tangential force and its variability) can be predicted from the equilibrium equations. Other phenomena could represent solutions preferred by the CNS. Among the latter: (a)

different locations of the clusters of the tangential force along the force-force lines in various tasks and in different subjects, (b) the lack of correlation between the total normal force and the moment that the force generates, and (c) a significant correlation between the thumb tangential force and the point of application of the normal virtual finger force. Individual performance variables are organized in two null spaces (uncontrolled manifolds). Variables within each null space highly correlate with each other (the coefficients of correlation are close to ± 1.0) while there is no correlation among variables from different uncontrolled manifolds. The discovery of the two null spaces supports the principle of superposition for human prehension (Arimoto et al. 2001).

References

- Arimoto, S., Tahara, K., Yamaguchi, M., Nguyen, P.T.A., and Han, H.Y. (2001) Principles of superposition for controlling pinch motions by means of robot fingers with soft tips. *Robotica* 19, 21-28.
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