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The principle of superposition in human prehension

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SUMMARY

The experimental evidence supports the validity of the principle of superposition for multi-finger prehension in humans. Forces and moments of individual digits are defined by two independent commands: “Grasp the object stronger/weaker to prevent slipping” and “Maintain the rotational equilibrium of the object”. The effects of the two commands are summed up.

Keywords

Superposition principle; Human prehension; Robotics

1. INTRODUCTION

One of the goals of this paper is to bridge the gap between the research on manipulation of hand-held objects (prehension) performed in robotics and in human movement science. Although both research areas can win from this cooperation, to the best of our knowledge, so far only a single study has applied the theories and methods developed in robotics to studying grasping in humans.[1]

As compared to the human hand, the grippers used in robotics are clumsy and inept. Nevertheless, research on human prehension can benefit from ideas generated in robotics. One of these ideas is the principle of superposition according to which some skilled actions can be decomposed into several elemental actions that are controlled independently by separate controllers.[2–4]

In particular, it has been shown that a dexterous grasp and manipulation of an object by two soft-tip robot fingers can be realized by a linear superposition of two commands, one command for the stable grasping and the second one for regulating the orientation of the object. In robotics, such a decoupled control decreases the computation time. This conclusion was based on the mathematical modeling and simulation of pinching objects by a thumb and the index finger. It is not known whether the principle of superposition is actually used by humans, especially when the grasping is performed with more than two digits.

2. METHODS

To test whether the control of finger forces during prehension uses the principle of superposition we performed two experiments. In the experiments the subjects held statically instrumented handles using prismatic grips. The task was similar to holding a glass filled with a liquid. The weight of the object and the magnitude of the resisted torque varied among the trials (the experimental setups, that were akin to the previously used by our group, are described in detail elsewhere).[5–7]

In the first experiment, the subjects (n=6) exerted the clockwise (negative) and counterclockwise torques of −1.0 Nm, −0.5 Nm, 0 Nm, 0.5 Nm and 1.0 Nm. The load was always 14.8 N. At each torque, the subjects performed 25 trials. The forearm, wrist and hand positions were fixed (Figure 1, right panel). The instruction to the subjects was to grasp the handle by placing the fingertip centers at the centers of the sensors and always apply a minimal effort. Finger forces and moments were recorded and the coordinates of the points of force application were computed. The analysis was limited to the planar static case; the forces of the fingers opposing the thumb were reduced to one resultant force [the virtual finger (VF) force].[8–11] The VF tangential force and VF normal force were computed as the sums of the tangential and normal forces of the fingers opposing the thumb, respectively. The moment of the normal forces was computed with respect to the point of application of the thumb force. The moment arm of the normal VF was computed from the Varignon theorem (Eq. 1)

$$D_{vf}^{n}=\frac{\sum F_{f}^{n}d_{f}}{\sum F_{f}^{n}} \tag{1}$$

where F_f^n is the normal force of finger f and d_f is the moment arm of the finger force with respect to the point of application of the thumb force (a projected distance from the point of application of a finger force to the point of application of the thumb force).

Using the data on the accuracy of individual sensors provided by the producer, the propagation of uncertainty in the measured finger forces to the uncertainty of the indirect measurements, e.g. the VF forces, was computed.[12] The Pearson coefficients of correlation were computed and then corrected for the uncertainty (noise) using Eq. 2.

$$\frac{r_x}{r_{x+n}}=\sqrt{\left(1+\frac{\sigma_{n1}^2}{\sigma_{x1}^2}\right)\left(1+\frac{\sigma_{n2}^2}{\sigma_{x2}^2}\right)} \tag{2}$$

where r_x is the coefficient of correlation between the variables x_1 and x_2 measured assuming the lack of errors (a ‘true’ coefficient), r_{x+n} is the coefficient of correlation between these variables when they are measured with errors (noise), σ_{n1} and σ_{n2} are the standard deviations of the errors of the first and second variables, respectively, and σ_{x1} and σ_{x2} are the standard deviations of the first and second variables measured without errors.

In the second experiment, both the loads and torques varied among trials (a 9 × 4 complete factorial design of experiment). The loads were 14.7 N, 19.6 N, 24.5 N and 29.4 N and the torques were −1.5 Nm, −1.125 Nm, −0.75 Nm, −0.375 Nm, 0 Nm, 0.375 Nm, 0.75 Nm, 1.125 Nm and 1.5 Nm, in total 36 combinations. At each load-torque combination subjects performed two trials. The results were averaged over the trials. Ten subjects took part in the experiments. Factorial repeated measure MANOVA was employed to analyze the effects of two factors – LOAD (four levels) and TORQUE (nine levels) – on ten outcome variables, the digit normal and tangential forces. The MANOVA’s tests of significance – Wilk’s, Lawley-Hotteling’s, and Pillai’s – were used.

3. RESULTS

The forces and moments which were exerted by the fingers on the hand-held object maintained statically in the air have been recorded and analyzed.

First experiment

Based on the correlations among the performance variables, all the performance variables belonged to one of the two subsets (Figure 2). The variables within each subset highly correlated with each other over repetitions of a task while the variables from different subsets did not correlate. The first subset included normal forces of the thumb and VF. The second subset included tangential forces of the thumb and VF, the moments produced by the tangential and normal forces, and the moment arm of the VF normal force D^n_{vf}. In particular, trial-to-trial changes of the VF normal force F^n_{vf} did not correlate with the variations of the moment of the normal force M^n_{vf} (Figure 2 A-2). Because the moment of the normal force is simply the product of the VF normal force and its moment arm, this lack of correlation is counter-intuitive. Contrarily, a high correlation between M^n_{vf} and the tangential force F^t_{th} was discovered (Figure 2 B-4). The high correlation between F^t_{th} and D^m_{vf} was also found (not shown in the figure).

Functionally, the fine-tuning of the variables of the first subset prevents the object from slipping out of the hand and from moving in the horizontal direction. Conjoint adjustments of the variables of the second subset maintain the torque and vertical orientation of the handle constant (they also prevent the object from moving in the vertical direction). Hence the data conform to the principle of superposition: Preventing the object from slipping out of the hand and maintaining the object orientation are controlled by two separate commands whose effects do not correlate with each other.

Second experiment

When the resisted load and torque changed in a systematic manner, the effects of LOAD and TORQUE on the finger forces – both normal and tangential – were highly significant ($p<0.001$). Conversely, the effects of the interaction LOAD × TORQUE on the normal and tangential forces were not significant ($p>0.6$). Figure 3 illustrates that the finger force changes associated with manipulation of one of the factors did not depend on the magnitude (level) of the other factor. The lack of the statistically significant interaction effects signifies the additive action of the LOAD and TORQUE commands.

4. CONCLUSION

The results of both experiments suggest that the principle of superposition is valid for the control of multi-finger prehension in humans. Forces and moments of individual digits are defined by two independent commands: “Grasp the object stronger/weaker to prevent slipping” and “Maintain the rotational equilibrium of the object”. The effects of the two commands are summed up.

Acknowledgments

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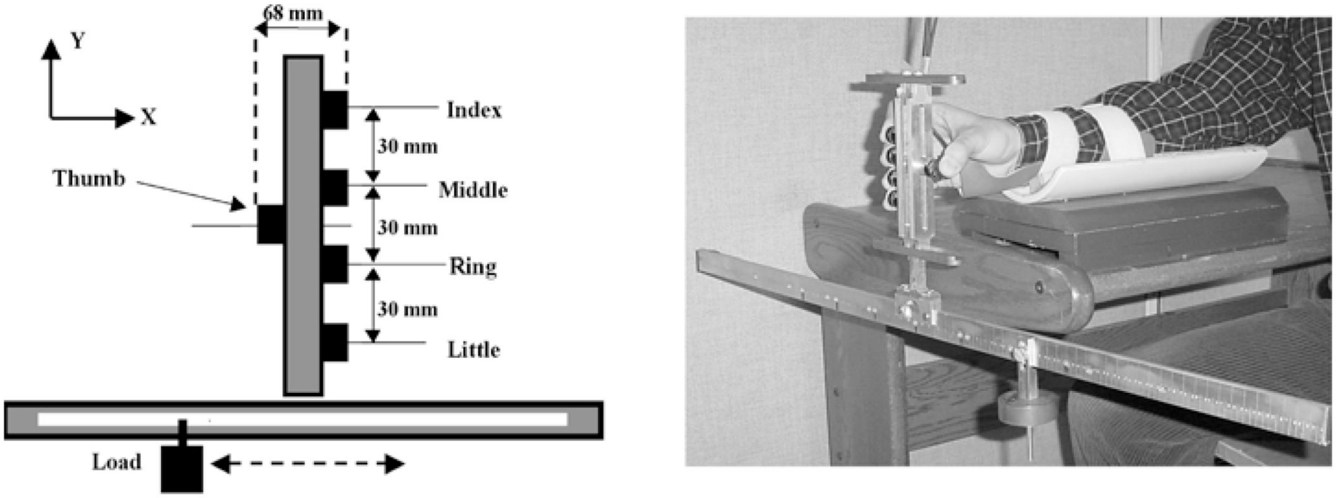

Fig. 1.

The experimental handle and the digit placement. Subjects maintained the handle statically in the upright position for 3 s. The load and/or torque varied across the trials. The torque varied by displacing the load along the horizontal beam. The black rectangles represent the 6-component force and torque sensors. The force components in the X and Y directions are called normal and tangential forces, respectively. In the first experiment the subjects grasped the handle with the thumb, index, middle and ring fingers. In the second experiments, they grasped the handle with all five digits. In both the experiments the thumb sensor was in the central position with respect to the working fingers. The moments of the normal finger forces were computed with respect to the point of application of the thumb force. The figure is not drawn to scale. (Right panel) The hand fixation. The forearm was strapped and the proximal part of the hand was supported by an Orthoplast-made brace that was individually molded to the hand shape. As a result the forearm and wrist movements were abolished and the handle position was standard over all trials.

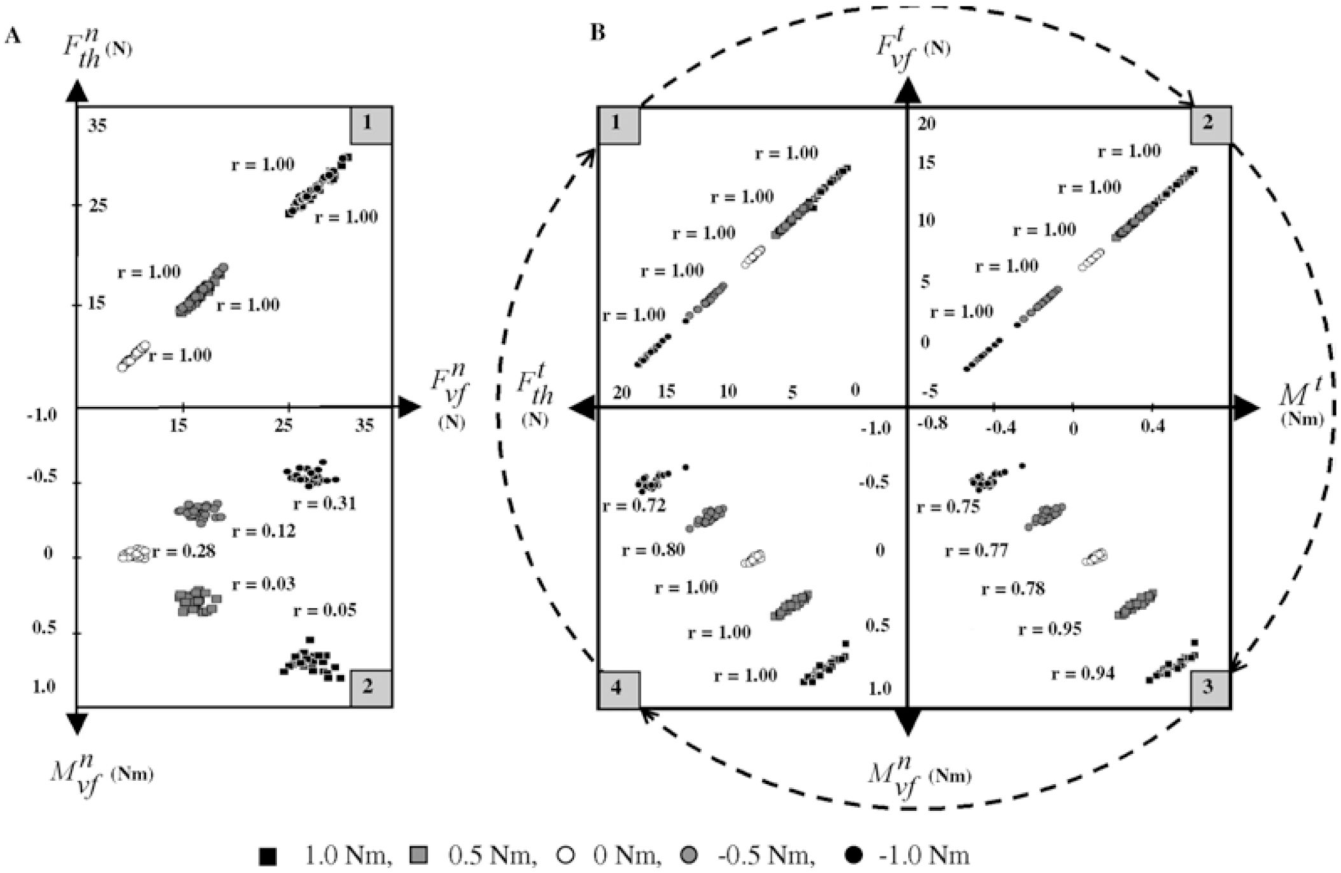

Fig. 2.

Interrelations among the experimental variables. Representative examples. *F* and *M* designate the force and moment; superscripts *n* and *t* refer to the normal and tangential force components; subscripts *th* and *vf* refer to the thumb and virtual finger, respectively. A-1: F^n_{th} correlated closely with F^n_{vf}. This correlation was expected: in static tasks F^n_{th} and F^n_{vf} cancel each other. These two forces represent the first subset of variables mentioned in the text. A-2: F^n_{vf} versus M^n_{vf}. The correlation coefficients are close to zero. B-1: F^t_{th} versus F^t_{vf}. The values of F^t_{th} and F^t_{vf} are on a straight line. This correlation was expected because $F^t_{th}+F^t_{vf}=\text{Constant (weight of handle)}$. The different location of F^t_{th} and F^t_{vf} values along the straight line signifies the different magnitude of M^t. B-2: F^t_{vf} versus $M^t[M^t=0.5(F^t_{vf}-F^v_{th})d, \text{ where } d=68\text{ mm}]$. As the sum F^t_{th} and F^t_{vf} is constant, a change in one of these forces determines the difference between their values and, hence, the moment that these force produce. B-3: M^t versus M^n_{vf}. B-4: M^n_{vf} versus F^t_{th}. The variables in the panels B (F^t_{th}, F^t_{vf}, M^t, M^n_{vf}) plus D^n_{vf} constitute the second subset of variables mentioned in the text. The arrows signify the sequence of events resulting in the high correlation between F^t_{th} and M^n_{vf} (‘chain effects’). Such a correlation does not exist between F^n_{vf} and M^n_{vf}, see panel A-2. The values of ‘true’ coefficients of correlations, i.e. the coefficients of correlation corrected for noise, are presented.

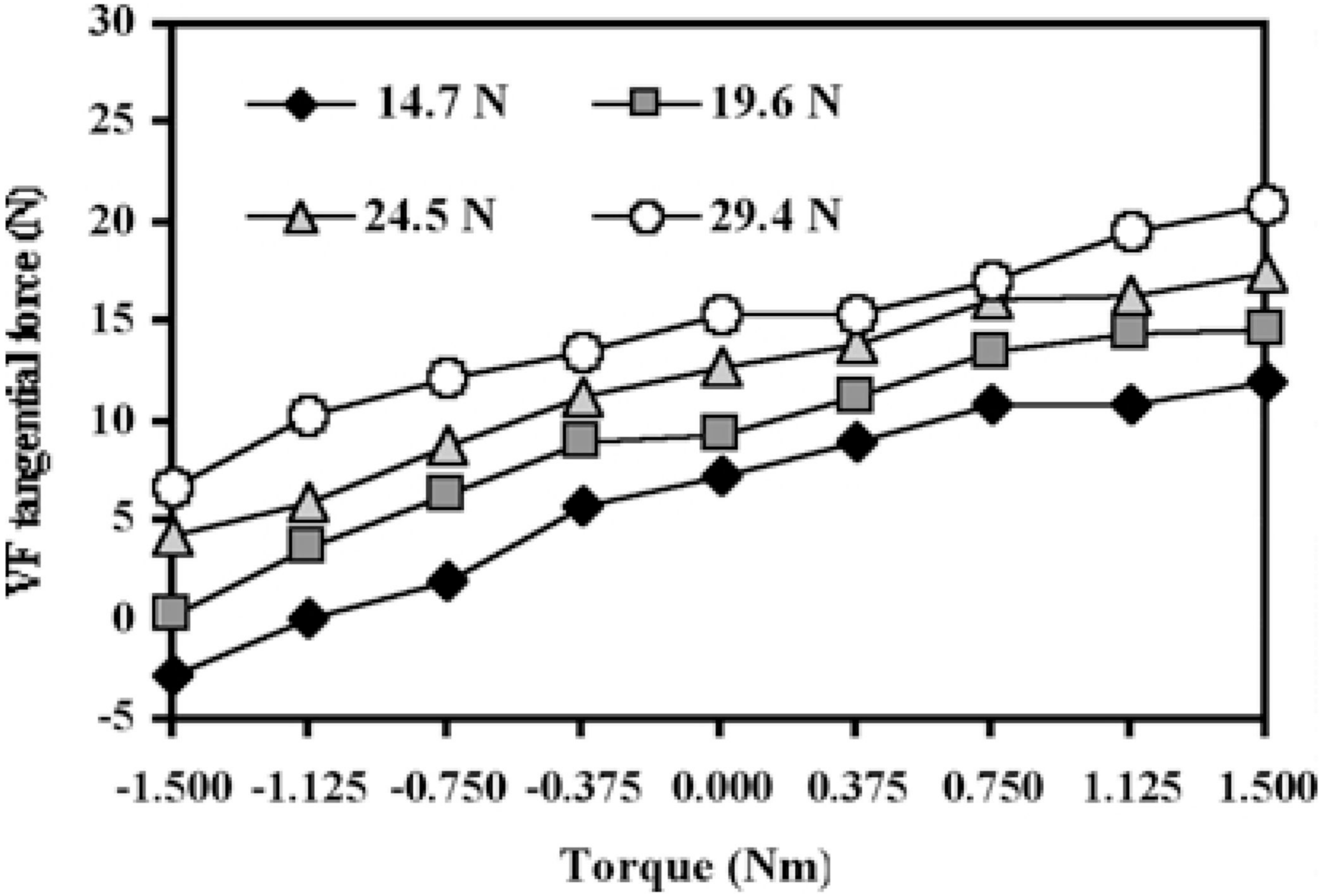

Fig. 3.

The VF tangential forces at the different magnitudes of the load and the resisted torque. Group average data (*n*=10). Note that the curves are almost parallel which signifies the lack of interaction between LOAD and TORQUE.