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Elaborate force coordination of precision grip could be generalized to bimanual grasping techniques

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Abstract

Exceptional coordination of grip (*G*; the normal force that prevents slippage of the grasped object) and load force (*L*; the tangential force originating from the object's weight and inertia) has been interpreted as a part of evidence that both the anatomy and neural control of human hands have been predominantly designed for manipulation tasks. In the present study, we tested the hypothesis that the *precision grasp* (uses only the tips of fingers and the thumb of one hand) provides better indices of G and L coordination in static manipulation tasks than two bimanual grasps (*palm–palm* and *fingers–thumb*; both using opposing segments of two hands). However, in addition to a subtle difference in relative timing of *G* and *L* between the precision and two bimanual grasps, we only found that the fingers–thumb grasp is characterized with higher *G*/*L* ratio and somewhat higher modulation of *G* than not only the precision, but also the bimanual palm–palm grasp. However, all remaining data including the correlation coefficients between *G* and *L* demonstrated no difference among three evaluated grasping techniques. Therefore, we concluded that the elaborate *G* and *L* coordination associated with uni-manual grasps could be partly generalized to a variety of manipulation tasks including those based on bimanual grasping techniques. Taking into account the importance of manipulation tasks in both everyday life and clinical evaluation, future studies should extend the present research to both other grasping techniques and dynamic manipulation conditions.

Keywords: Human; Movement control; Isometric; Oscillatory; Manipulation; Bimanual

To hold and manipulate an object we have to grasp it and apply a grip force to achieve the manipulation goals and prevent slippage. During the hand-object interaction, a number of the object's properties and ongoing movement related events should be taken into account, such as the size, shape and weight of the object, inertial load caused by acceleration, or the coefficient of friction acting at the contact surface. The final result is an elaborate coordination of the grip force (*G*) with respect to the load force (*L*), which tends to cause slippage. For example, *G* is accurately adjusted to friction acting at the contact surfaces and only slightly exceeds the minimal value required to prevent slippage [6,11]. Changes in *L* caused either by inertial forces acting due to the acceleration of the hand-held object or by exertion of *L* against an externally fixed object are associated with a high and simultaneous modulation of *G* that not only prevents the slippage but also keeps a stable grip-to-load (*G*/*L*) ratio [2,8,10,11,20–22]. Based on these observations, it has been concluded that the coordination of *G* and *L* is controlled by predictive, feed-forward mechanisms [11].

Not surprisingly, various neurological patients with impaired hand function consistently demonstrate elevated grip force (leading to excessive *G*/*L* ratio), as well as a poor coupling of *G* with the changes in *L* and/or delayed adjustment of *G*, which inevitably leads to both a low *G* modulation and low correlation between *G* and *L* (see [15] for review). Similarly, an increase in task complexity, such as switching from the tasks that require *L* exerted only in one direction to bidirectional tasks, or involving non-homologous muscles of two arms into a manipulative action, also lead to both a reduced and irregular modulation of *G* with respect to *L*, as well as to an increased *G*/*L* ratio [10,19].

There are a number of general arguments suggesting that such an elaborate coordination of *G* and *L* observed in healthy individuals should not be considered as a surprise. Mechanically, hand represents the most complex 'machinery' within our locomotor apparatus. There is a strong evidence that the evolutionary

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changes in hand morphology in early humans were "ultimately yielding a grasping, prehensile hand" [7]. Regarding the motor control aspects, the size of the neural representation of hand in various cortical areas is only paralleled with the mouth region. While the proximal musculature of the arm is mainly subjected to bilateral cortical control, the distal muscles of the hand involved in exerting *G* are predominantly exposed to contralateral control presumably providing independent actions of two hands [1]. As a result, both the dexterity and repertoire of hand activities (e.g. when playing musical instruments or manipulating tools) exceed by far all other activities of the human locomotor apparatus. However, most of the research has been focused on the tasks that hands seem to be predominantly designed for. Specifically, those are the tasks based on single hand grasps, such as precision and pinch grasp (i.e. the objects are controlled by the tips of digits), or power grasp. McDonnel et al. recently demonstrated that when switching from the precision grip to other grasping techniques performed with the same hand could be associated with a decreased coordination of *G* and *L* [13]. However, in our everyday life we often grasp and manipulate objects and tools not only bimanually, but also using different hand segments, such as palms. Mechanically, these activities also require accurate adjustment of 'grip' force (normal component of force that prevents slippage) with the changes in *L*. Therefore, the main aim of the present study is to explore whether and to what extent are the properties of coordination of *G* and *L* affected by switching from the precision grasp to other grasping techniques that include actions of two hands. Based on the rationale presented above, we hypothesized that the precision grasp will demonstrate an advantage over various bimanual grasping techniques. In line with the previous findings, we expected that this advantage will be reflected in lower *G*/*L* ratio, higher modulation of *G*, as well as higher correlation coefficients between *G* and *L*.

Twelve healthy human volunteers (5 women and 7 men, 22–32 years of age) participated in the study. The experimental procedure was conducted in accordance to Declaration of Helsinki and approved by the Human Subjects Review Board of the University of Delaware. The participants were tested on bimanual manipulation tasks performed under isometric conditions. The experimental device used in this study (see Fig. 1A) consists of two externally fixed vertical handles covered with rubber with a 3 cm aperture and positioned 13 cm apart. Two force transducers (miniature single-axis strain gauge load cells WMC-50, Interface Inc.) allowed simultaneous recording of grip (*G*) forces of each hand applied against the handles. An additional pair of multi-axis force transducers positioned below each handle (Mini40, ATI, Apex, NC) were used to record forces exerted in vertical direction (load force; *L*). The device was fixed in front of a standing participant and the height was individually adjusted for each participant to position the handles just above the waist level.

The experimental procedure was conducted within a single session. Prior to the main experiment the participants cleaned their hands with alcohol swab and dried them with paper tissue. Thereafter, the maximum pinch *G* exerted by tips of all 5 digits of each hand was separately recorded. Twelve percent of the maximum pinch *G* of the weaker hand served later on as instructed peak *L* in the main experiment. According to previous findings, this level was well below the one that could cause fatigue [9,12]. As a result, the maximum level of the prescribed *L* was participant specific and ranged from 5 to 13 N. After having their maximum pinch *G* measured, the participants were submitted to a familiarization procedure practicing experimental tasks over approximately 30 min. Finally, within the main part of the experiment, the participants exerted *L* in vertical direction producing an oscillatory pattern paced by a metronome set to 2 Hz (i.e. two full oscillations per second). The average *L* exerted by the participant's right and left hand was depicted on a computer screen serving as feedback. *G* was not mentioned through the entire experiment.

Within six consecutive trials performed in random sequence the subjects were instructed to grasp the handles of the device and exert the prescribed pattern of *L* under different 'grasp' and 'direction' conditions. In particular, participants used three different grasping techniques while mimicking exerting the instructed *L* against an externally fixed object. In the *precision grasp* the tips of all five digits applied the force against the handles of the device (see Fig. 1A and the left hand side Fig. 1B for illustration). In the *palm–palm grasp* participants pressed the handles with centers of their palms medially (see middle part of Fig. 1B). In the *fingers–thumb* grasp participants pressed the closer handle with the right thumb in anterior direction and the

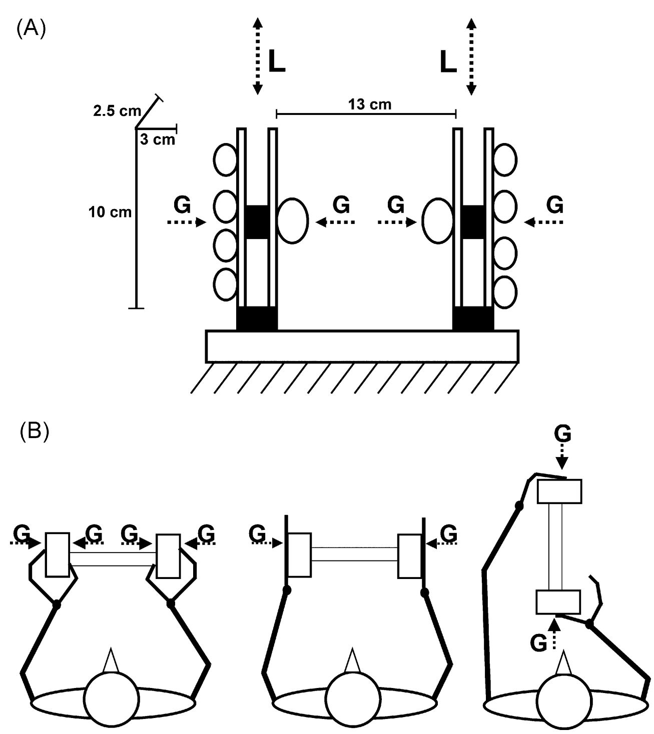

Fig. 1. (A) Schematic representation of the experimental device. The circles illustrate the position of the tips of all five digits applying precision grasp against two handles. The lower shaded rectangles illustrate the force sensors recording the instructed load force (*L*) exerted in vertical direction, while the upper ones recorded the grip force (*G*). (B) The stick diagrams illustrate the horizontal projections of the applied precision grasp (left hand side; this grasp is also illustrated in (A), palm–palm grasp (middle), and the fingers–thumb grasp (right hand side), as well as the corresponding *G*.