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

Paulo Barbosa Freitas Jr., Vennila Krishnan, Slobodan Jaric *

Department of Health, Nutrition, and Exercise Sciences, University of Delaware, Newark, USA

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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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* Corresponding author at: Human Performance Laboratory, University of Delaware, 547 S. College Av., Newark, DE 19716, USA. Tel.: +1 302 8316174; fax: +1 302 8313693.

E-mail address: jaric@udel.edu (S. Jaric).

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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

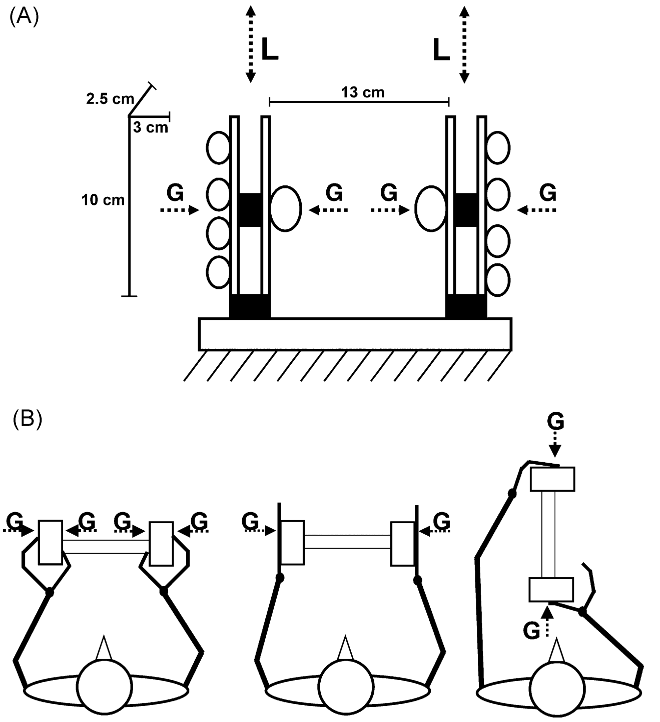

Fig. 1. (A) Schematic representation of the experimental device. The circles illustrate the position of the tips of all five digits applying precision grasp against two handles. The lower shaded rectangles illustrate the force sensors recording the instructed load force (L) exerted in vertical direction, 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.

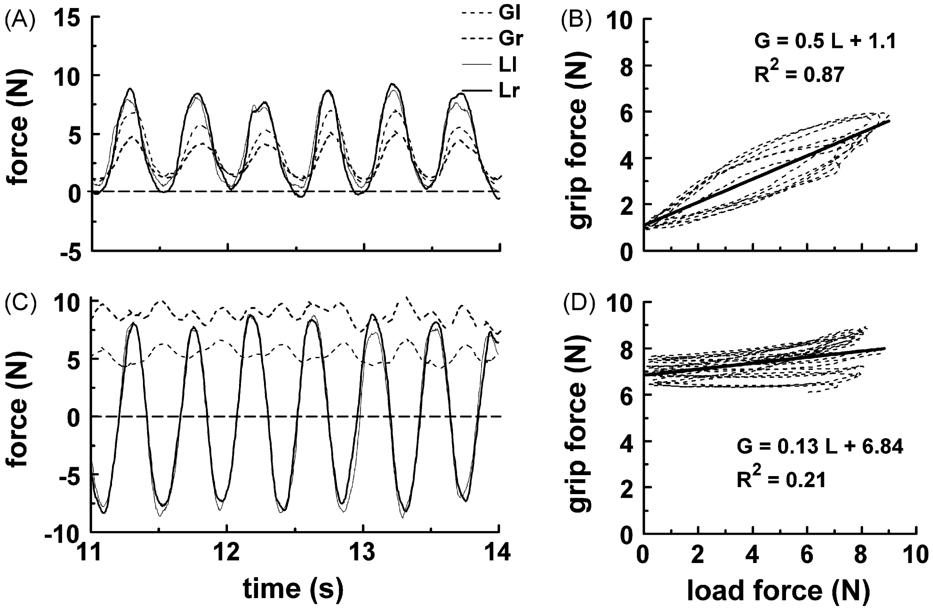

Fig. 2. Grip (G; dashed lines) and load (L; solid lines) forces of the right (r; thick lines) and left hand (l; thin lines) recorded in a representative subject while using the palm–palm grasp in unidirectional (A) and bidirectional task (C). The right hand panels (B and D) represent the corresponding grip-load diagram depicted with regression lines and correlation coefficients.

distant handle with the tips of all four fingers of the left hand in the posterior direction (Fig. 1B, right hand side). In addition to three different grasping techniques, the participants were also tested under different 'direction' conditions by exerting either the *unidirectional* (i.e. pulling handles vertically up and relaxing) or *bidirectional* L (consecutively pulling up and pushing down). Under both conditions the subjects were instructed to exert L between two depicted horizontal lines that, therefore, indicated the maxima (corresponds to the maximum of the pulling-up force) and minima (corresponds to zero L in unidirectional and to maxima of pushing down L in bidirectional tasks).

Each trial lasted 16 s. The first 10 s (considered as an adjustment phase) and the last 1 s were omitted and, consequently, the 5 s interval (i.e. data recorded between the 10th and 15th second; containing approximately 10 full oscillations) remained for further analysis. Signals from four force transducers were recorded at a sampling frequency of 200 Hz and low-pass filtered (10 Hz). Because all three grasps were designed to mimic isometric action against an externally fixed object, we averaged G and L exerted by two hands. Since the direction of L does not affect the G required to prevent slippage, we performed data analysis on rectified L (see [9,10] for the same approach). Repeated measures ANOVAs were used to test the effects of grasp (precision versus palm–palm versus fingers–thumb) and direction (uni- versus bidirectional task) on all dependent variables. Appropriate post hoc tests were carried out, when necessary.

Fig. 2 illustrates the recorded forces in two trials of a representative subject performed with the palm–palm grip. While the top left panel shows a unidirectional task (participant was consecutively pulling both handles up and relaxing; Fig. 2A), the bottom left panel illustrates a bidirectional task (consecutively pulling up and pushing down; Fig. 2C). Note that two hands generally demonstrate a similar level of involvement regarding the magnitude of their L, as well as that all four forces are highly coupled with no discernible time lags among them. However, note also that switching from unidirectional to bidirectional task is associated with both an increased level of G and a decrease in G/L modulation. These changes should lead to an increased G/L ratio, as well as a decreased correlation between G and L. The right hand side graphs depict G–L force diagrams representing the data shown on the corresponding left hand side after averaging two lateral G and L. When compared with the unidirectional task (Fig. 2B), a lower modulation of G observed in the bidirectional task (Fig. 2D) is associated with both a low slope and high intercept of the regression lines (interpreted as G gain and offset, respectively), as well as with a low correlation coefficient observed between G and L.

To assess how accurately the tasks were performed, we calculated constant and variable errors from the consecutive peaks of L. Virtually all constant errors were below 1 N, showing no main effects or interactions. Variable errors (averaged across the subjects) were also well below 1 N. A two-way ANOVA demonstrated no main effects of grasp and no interactions. Only the bidirectional task showed higher variable error than the unidirectional task (0.86 ± 0.21 versus $0.50 \pm 0.\ 45$ N, $F[1,11] = 19$; $p < 0.01$).

Regarding the indices of G and L coordination, as a first step we calculated grip-to-load (G/L) ratio from the average values of G and L assuming that lower ratio was an index of better coordination. The results revealed the main effects of grasp ($F[2,22] = 12.6$; $p < 0.01$), and direction ($F[1,11] = 43$; $p < 0.01$), and no interaction. As indicated in Fig. 3A, G/L ratio was higher in the fingers–thumb than in the remaining two grasps, as well as higher in bi- than in the unidirectional task.

Based on previous research (see introductory paragraphs), both the high values of the maximum correlation coefficients

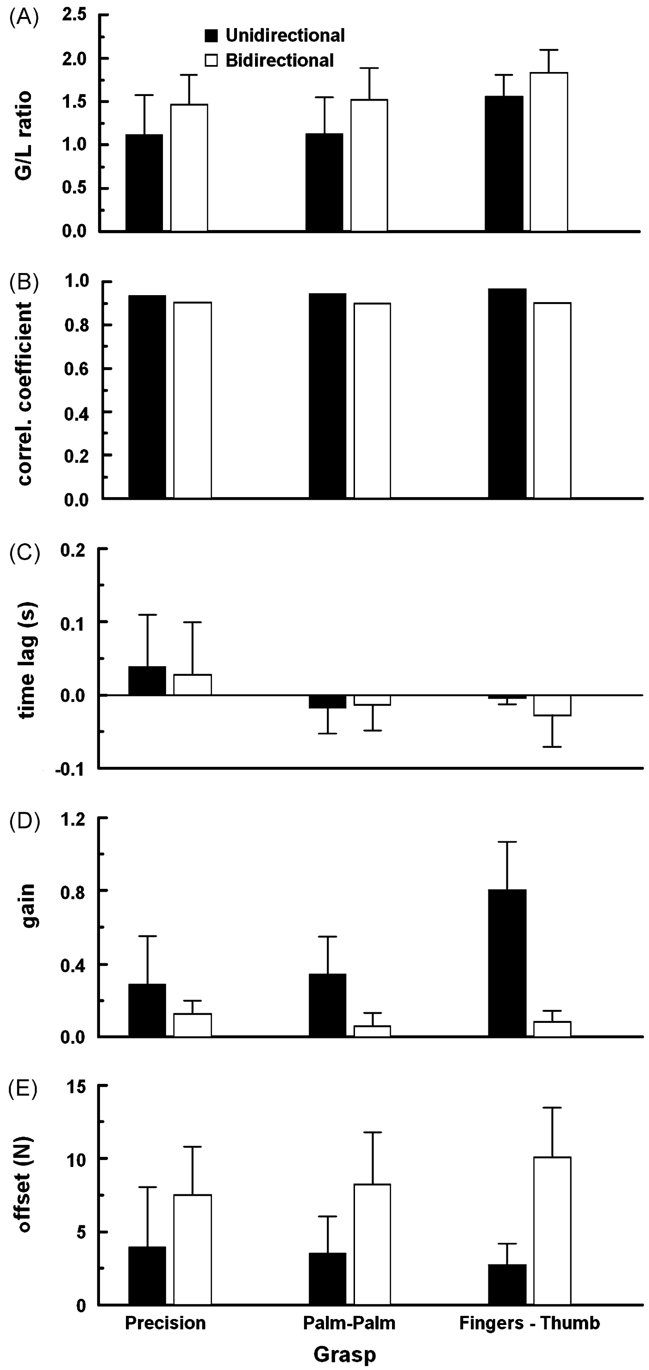

Fig. 3. Averaged across the subjects G/L ratios (A), median values of maximum correlation coefficients between G and L (B), the corresponding time lags (C), and G gains (D) and G offsets (E) observed under different grasp and direction conditions. Positive time lags denote G preceding L. Error bars depict standard deviations.

and low time lags obtained from the cross correlations between G and L should indicate higher force coordination. The maximum correlation coefficients were remarkably high under all conditions, as illustrated by their median values depicted in Fig. 3B. The Z-transformed values revealed the main effects of direction ($F[1,11]=15$; $p<0.01$), but not of grasp and no interaction. As illustrated in Fig. 3B, unidirectional task was associated with higher correlation coefficients than the bidirectional one. Regarding the time lags between G and L, the values were close to zero suggesting anticipatory neural mechanisms controlling the coordination of G and L (see Fig. 3C). Nevertheless, the positive lags indicate that G slightly preceded L when the precision grasp was applied, but not in the two bimanual grasps. As a result, two-way ANOVA revealed only the main effect of grasp ($F[2,22]=8.8$; $p<0.01$; the precision grasp revealing higher time lags than the remaining two grasps), but not of direction and no interaction.

Finally, in line with a number of previous studies [6,8,22] we assessed the modulation of G by calculating the regression lines from G–L diagrams (see Fig. 2C and D for illustration). In general, a high level of modulation of G with respect to changes in L was expected to be revealed by both a high G *gain* (corresponds to the slope of the regression line) and a low G *offset* (corresponds to the intercept). Regarding the G gain, the results revealed the main effect of grasp ($F[2,22]=16$; $p<0.01$), direction ($F[1,11]=120$; $p<0.01$), and the grasp × direction interaction ($F[2,22]=16$; $p<0.01$; see Fig. 3D). Specifically, a higher G gain was observed uni- than in the bidirectional task, while the fingers–thumb revealed a higher G gain in uni-, but not in the bidirectional task. Finally, the G offset revealed the effect of direction ($F[1,11]=124$; $p<0.01$), and the grasp × direction interaction ($F[2,22]=9.5$; $p<0.01$; see Fig. 3E). In particular, the G offset was higher in bi- than in unidirectional task, while the fingers–thumb grasp demonstrated somewhat higher G offset in bi- but not in unidirectional task.

In general, the results revealed both high correlation coefficients and low time lags between G and L that were comparable to other studies based on free movement or isometric manipulation tasks [6,8,22]. The obtained effect of direction was also in line with previous studies performed on either free movements or isometric actions. In particular, switching from uni- to bidirectional production of L was associated with a deteriorated coordination of G and L reflected in increased G/L ratio, decreased correlation coefficients between G and L, and a decreased modulation of G revealed in both a low gain and high offset [6,10]. Therefore, the remaining part of the discussion will be focused on the main finding of our study related to the effect of grasp on the G and L coordination.

Based on a number of general considerations we hypothesized that the precision grasp would demonstrate higher level of force coordination than the remaining two bimanual grasping techniques. The later ones were not only based on joint actions of two hands (instead of 'naturally' grasping the object with one hand, as in the precision grasp), but also either manipulated the 'object' pressing it with the middle section of palms instead with the finger tips (the palm–palm grasp), or using the fingers and thumb of the opposing hands acting in the anterior–posterior direction and, therefore, involving non-homologous muscles to produce G (the fingers–thumb grasp). However, in addition to a subtle difference in relative timing of G and L between the precision and two bimanual grasps, we found that the fingers–thumb grasp is characterized with higher G/L ratio and lower 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, it appears that the most of the findings do not support the hypothesized advantage of the precision grasp over the evaluated bimanual grasps. This outcome could be somewhat surprising, particularly when taking into account potential advantages of uni-manual grasps that could be deduced from not only the anatomical and neurophysiological, but also evolutionary aspects (see introductory paragraphs for details).

A plausible interpretation of the observed findings could be based on a generalization of the evaluated neural control mechanisms. Although hands appear to be anatomically designed for a uni-manual grasp where the fingers oppose the thumb of the same hand (e.g. precision, pinch, or power grasp), the neural mechanism that provide a well documented elaborate *G* and *L* coordination could be also generalized to coordination of the normal force (corresponds to *G* and prevents slippage) and tangential force (*L*) in a variety of other grasping techniques. These techniques could include both those used in bimanual manipulation of larger objects and the manipulations requiring simultaneous actions of non-homologous muscles of two hands and arms. However, the time lags suggest that the aforementioned generalization could be only a partial one. A small but detectable lag of *L* with respect to *G* we observed in the precision grasp that could be interpreted as a safety factor that prevents slippage in uni-manual manipulation [4,5,11] was absent in the remaining two bimanual grasps.

Flanagan and Tresilian [3] evaluated *G* and *L* coordination in lifting task under a variety of uni- and bimanual grasping techniques. Although inconsistent findings obtained from four tested subjects prevented them from statistical evaluation, the results indicated a remarkably high ratio of *G* and *L peaks* in some bimanual grasps (as compared to uni-manual ones), while the corresponding correlation coefficients seemed to be mainly unaffected. Nevertheless, the authors speculated that the studied *G* and *L* coordination could represent a general control strategy, rather than a specific one for a particular grasping technique. We found that under static conditions most of the indices of an elaborate coordination of *G* and *L* well known to characterize the standard precision grasp could be generalized to bimanual grasping techniques. Taking into account the exceptional importance of manipulation tasks in both everyday life and clinical assessment, further research is needed to answer a number of questions regarding the role of grasping technique in force coordination. For example, we recently demonstrated partly different coordination of *G* and *L* under static as compared with dynamic conditions [8], while a relatively weak effect of switching from precision to bimanual grasp contradict results obtained from free lifting tasks [3]. Therefore, extension of our approach to the free movement tasks deserves further attention. Role of skin receptors in force coordination also represents a well documented phenomenon [11,16]. All three grasping techniques applied in this study used hand areas with the exceptionally high density of these receptors (i.e. the tips of fingers and thumbs, and the palm) for the contact. Therefore, it remains possible that using the hand sections with a lower receptor density for grasping (e.g. dorsal areas of fingers and hand) would provide deteriorated indices of force coordination (e.g. high *G*/*L* ratio and low coordination of *G* and *L*) similar to those observed from subjects with reduced sensibility from the grasping digits [14,17]. Finally, since the grasping surfaces were both parallel and vertically oriented, it also remains possible that an increased complexity of the task imposed by either an asymmetric grasping surface or eccentric loading force relative to the surface [18] could still reveal differences among the evaluated grasping techniques.

Acknowledgments

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