Exp Brain Res (2008) 185:111–119
DOI 10.1007/s00221-007-1136-4

RESEARCH ARTICLE

An object for an action, the same object for other actions: effects on hand shaping

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Received: 26 June 2007 / Accepted: 12 September 2007 / Published online: 2 October 2007

Abstract Objects can be grasped in several ways due to their physical properties, the context surrounding the object, and the goal of the grasping agent. The aim of the present study was to investigate whether the prior-to-contact grasping kinematics of the same object vary as a result of different goals of the person grasping it. Subjects were requested to reach toward and grasp a bottle filled with water, and then complete one of the following tasks: (1) Grasp it without performing any subsequent action; (2) Lift and throw it; (3) Pour the water into a container; (4) Place it accurately on a target area; (5) Pass it to another person. We measured the angular excursions at both metacarpal-phalangeal (*mcp*) and proximal interphalangeal (*pip*) joints of all digits, and abduction angles of adjacent digit pairs by means of resistive sensors embedded in a glove. The results showed that the presence and the nature of the task to be performed following grasping affect the positioning of the fingers during the reaching phase. We contend that a one-to-one association between a sensory stimulus and a motor response does not capture all the aspects involved in grasping. The theoretical approach within which we frame our discussion considers internal models of anticipatory control which may provide a suitable explanation of our results.

Keywords Reach-to-grasp · Hand shaping · Internal models · Action planning · End-goal

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Introduction

The study of grasping movements was considerably advanced by Napier's (1956) landmark work. His model went far beyond the on line requirements of grasping movements and highlighted the importance of action goals in determining different hand movements. In Napier's (1956) words "this diversity (of the prehensile activities of the hand) is in fact not so much an expression of a multiplicity of movements but of the vast range of purposive actions involving objects of all shapes and sizes that are handled during everyday activity" (p. 904).

Since these early qualitative observations, grasping has been widely investigated in both humans and monkeys with a variety of tasks and techniques (for review see Castiello 2005). Surprisingly, there has been little research on how actors shape their hands while reaching toward an object that takes into consideration the reason why that very same object is moved.

For instance, Cohen and Rosenbaum (2004) asked participants to take hold of a cylindrical object and move it to a new position. They found that the grasp heights on the cylinder were inversely related to the height of this new position. This result was taken as evidence that actors anticipate the positions they will comfortably adopt upon completing object transport movements. In other words, the part of the object that people grasp can give insight into the planning of movement. Similarly, Eastough and Edwards (2007) showed that knowledge of the weight of a to-be-grasped object can affect prior-to-contact grasp action kinematics and the placement of the fingers upon the object. Heavy, as compared to light, objects caused increased peak grasp aperture and a final finger and thumb placement on the object that more closely passed through the object's centre of mass. The influence of different consecutive movements on initial reaching and prehension movement was also examined by Armbrüster and Spijkers (2006). They considered four after-grasp movements differing in direction and accuracy requirements: lifting, raising, throwing, and placing. Their results showed that movement parameter values were affected by the type of subsequent movement. Specifically, peak aperture was larger and peak deceleration was higher when the grasp was followed by either a throwing or a placing movement than by the lift and raise conditions. These findings suggest that the reason why an object is grasped has an effect on initial prehension kinematics. Ansuini et al. (2006) added a level of complexity to this analysis by not only investigating the grasp component at the level of two-digit kinematics (i.e., index finger and thumb) but also by considering whether the angular excursion of individual fingers varied depending on the accuracy requirements of the action that follows the grasping of the object. By asking participants to grasp the same object and either lift it and fit it into a tight or a large niche, they showed that the degree of end-goal accuracy did affect hand shaping during the approach phase.

Altogether, the above mentioned results strongly suggest that human hand movements are characterized by the use of a movement form associated with the action end-goal. However, in order to shed more definite light on this issue, a paradigm is needed that addresses two questions which so far have remained untested. First, whether hand shaping varies depending on the presence or absence of an action beyond grasping. The second, and interconnected question, is whether what is to occur after, or ‘beyond grasping’, elicits specific patterns of hand shaping. Findings from previous studies do not answer these questions because subsequent action and end-goals were only varied along one dimension (e.g., accuracy) within the same class of tasks.

We addressed these questions by asking participants to perform five tasks involving the same object: grasp it; grasp and throw it into a container; grasp and place it accurately on a base matching its diameter; grasp and pour the water inside the object into a container; and grasp and put it into the hand of an another person. The rationale behind implementing these particular tasks was the following: the grasp condition served as a baseline to identify the ‘beyond grasp’ effect. The passing and placing actions were accurate conditions which differed in terms of the after-grasp movement direction. The throwing action represented an example of a low-accuracy condition. Finally, the pouring action was considered as it implies a wrist rotation which added a level of complexity in terms of planning.

The effect of the a-specific presence of an action beyond grasping will be revealed by the comparison between hand shaping for the grasping task and the tasks involving a subsequent action. Any specific ‘beyond grasping’ effects will be revealed by comparing hand shaping across tasks including subsequent actions.

Material and methods

Subjects

Twenty subjects (ten females and ten males, ages 20–30 years, mean age 24.5 years) took part in the experiment. All participants were right-handed and reported normal or corrected-to-normal vision. All subjects were naïve as to the experimental purpose and gave informed consent to participate in the study. The experimental procedures were approved by the Institutional Review Board at the University of Padua and were in accordance with the declaration of Helsinki.

Stimulus and apparatus

The target object was a plastic bottle filled with 350 ml of water and located at 30 cm from the hand starting position (Fig. 1). The target object was placed on a pressure switch embedded within the table surface and located at 35° to left of the hand starting position (see Fig. 1).

Procedures

The participant sat on a height-adjustable chair in front of a rectangular table with the elbow and the wrist resting on the table, the forearm horizontal, the arm oriented in the parasagittal plane passing through the shoulder and the right hand on the starting position (Fig. 1). The hand was pronated with the palm toward the table on a pressure switch. To make sure that the hand starting position was similar for all participants across trials, the surface within which the pressure switch was embedded was designed with slight convexities dictating a natural flexed posture of the fingers (Fig. 1). Participants naturally reached toward and grasped the target object opposing the thumb to the four fingers of her/his right hand after hearing an auditory signal (Hz = 880; duration = 200 ms). This task had to be performed under five different experimental conditions:

(1) ‘Grasp’ condition: participants were requested to reach toward and grasp the target object. No further action was requested.
(2) ‘Throw’ condition: participants were requested to reach toward, grasp the target object, lift it and throw it into a cardboard container (depth = 19 cm; width = 30 cm; height = 9 cm). The container was located on a 23-cm high platform (depth = 21 cm; width = 33 cm). This platform was placed 5 cm behind the base of the object (see Fig. 1).

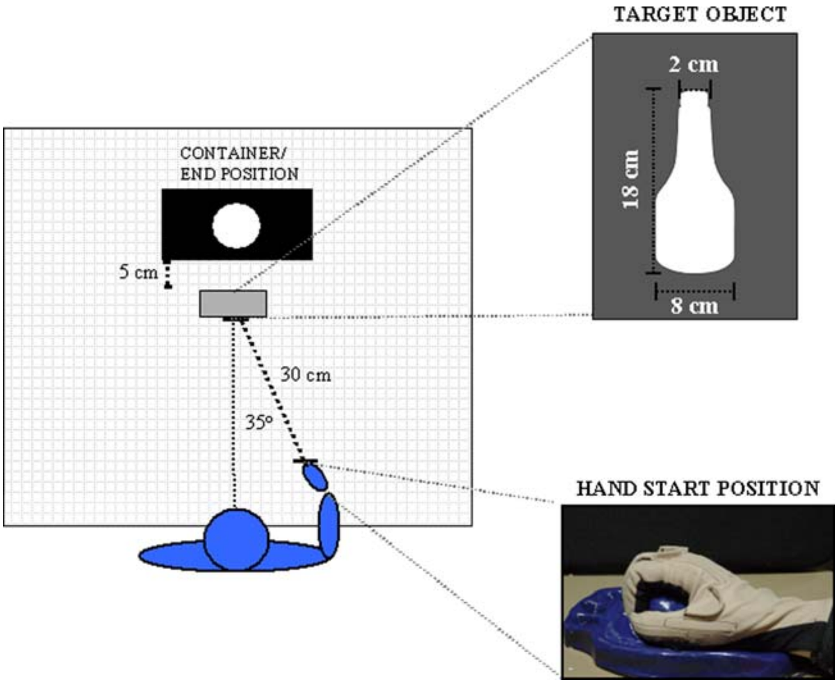

Fig. 1 Top view of the experimental setup (not to scale), the object used as a target and the hand starting position adopted by each subject at the beginning of each trial

(3) 'Place' condition: participants were requested to reach toward, grasp the target object, lift it, and place it precisely within a drawn circle perfectly matching the diameter of the base of the bottle. The circle was drawn at the center of the top of the container (Fig. 1). The container was the same used for the 'throw' condition.

(4) 'Pour' condition: participants were requested to reach toward, grasp the target object, lift it, and pour the water into a plastic container. The object was re-filled after each trial as to maintain the same weight for all conditions.

(5) 'Pass' condition: participants were requested to reach toward, grasp the target object, lift it, and pass it to the experimenter.

The centeroid of the location at which we located the cardboard container (condition no. 2), the circle (condition no. 3), the plastic container (condition no. 4), and the experimenter's hand (condition no. 5), was kept constant across conditions.

A block of 50 experimental trials, which included 10 trials for each of the five experimental conditions, was administered. Trials of different types were randomized within the block. Before the start of each trial, subjects were informed about the action to be performed and a block of ten practice trials (two examples for each type of experimental condition) was administered. To avoid fatigue and lack of concentration/attention, subjects were given a pause every ten trials.

Recording techniques

Hand posture was measured by resistive sensors embedded in a glove (CyberGlove, Virtual Technologies, Palo Alto, CA, USA) worn by the subjects on the right hand. The linearity of the sensor was 0.62% of maximum nonlinearity over the full range of hand motion. The sensor resolution was 0.5° which remains constant over the entire range of joint motion. The output of the transducers was sampled at 12-ms intervals. Angular excursion was measured at metacarpal-phalangeal (*mcp*) and proximal interphalangeal (*pip*) joints of the thumb, index, middle, ring, and little fingers (T, I, M, R, and L, respectively). Before starting the experiment, we recorded the baseline hand posture by asking subjects to position their right hand flat on the table and to maintain it in that position while *mcp* and *pip* joints' angles of all digits were recorded. The *mcp* and *pip* joints' angles were defined 0° when the fingers were straight in the plane of the palm ('baseline' hand posture), and flexion was assigned positive values. The 'baseline' abduction angles of adjacent digit pairs were set as 0° when the hand was positioned flat on a pre-determined position ('baseline' hand posture) with pre-set abduction angles (thumb-index finger = 22°; index-middle fingers = 32°; middle-ring fingers = 45°; ring-little fingers = 50°). Angle closure was assigned negative values. At the beginning of each trial, the subject's wrist contacted a pressure switch whose release indicated onset of the reaching movement. For all conditions, except that for the 'grasp' condition, reach duration was calculated as the time interval from the release of the starting switch and the time at which the switch underneath the target object was released. For the 'grasp' condition, which did not imply a subsequent action, reach duration was determined off-line as the time at which at least ten over the 14 recorded sensors remained stationary for at least five temporal samples.

Data analysis

To test for possible differences in reach duration as a function of experimental condition an analysis of variance (ANOVA) with ‘Functional Goal’ (‘grasp’, ‘throw’, ‘place’, ‘pour’, ‘pass’) as within-subjects factor was performed. To assess how and to what extent the angular excursion at the analyzed joints for each digit differed across experimental conditions, relative values for the dependent measures of interest were entered into ten repeated measures ANOVAs, one for each of the two joints (i.e., *mcp* and *pip*) for each digit separately. The within-subjects factors were ‘Functional Goal’ (‘grasp’, ‘throw’, ‘place’, ‘pour’, ‘pass’) and ‘Time’ (from 10 to 100% of the reach, at 10% intervals). Similar analyses were conducted to ascertain the effect of the experimental condition on each of the considered abduction angles (i.e., thumb–index, index–middle, middle–ring, and ring–little fingers). Simple effects were used to explore the means of interest. Bonferroni corrections (alpha level: $P < 0.05$) were applied.

Results

Reach duration

As depicted in Fig. 2, reach duration was significantly affected by both the presence and the type of action following grasping (i.e., main effect of ‘Functional Goal’, [$F(4,76) = 163.374$, $P < 0.0001$]. In the first instance, when a subsequent action was not requested (i.e., ‘grasp’ condition) reach duration was longer than for all the other conditions (1,068 ms; $P_s < 0.05$; see Fig. 2). In the second instance, except for the comparison between the ‘pour’ and the ‘place’ conditions, significant differences were found when comparing reach duration across the other conditions ($P < 0.05$; Fig. 2). As depicted in Fig. 2, the shortest reach duration was associated with the ‘throw’ condition (768 ms). The ‘pass’, the ‘place’, and the ‘pour’ conditions were significantly longer than the ‘throw’ condition (883, 988, and 988 ms, respectively; $P_s < 0.05$). However, similar values were found for the ‘place’ and the ‘pour’ conditions ($P > 0.05$).

Angular excursion at individual fingers’ joints

Table 1 shows the results of the ANOVAs performed on the angular excursion at individual fingers’ joint. As revealed by the interaction ‘Functional Goal’ by ‘Time’ for both *mcp* and *pip* joints of all digits, the posture assumed by individual fingers’ joint during reaching was significantly affected by both the presence and the type of subsequent actions. In particular, an effect due to the presence of a subsequent action was evident from 20 up to 50% of reach duration for both *mcp* and *pip* joints for all digits. As depicted in Fig. 3, they were more extended for the ‘grasp’ than for the other conditions. However, after 50% of reach duration, an inversion of this pattern was particularly evident for both *mcp* and *pip* joints of the thumb and the index finger and for the *mcp* joint for both the middle and the ring fingers (see Fig. 3). At these joints a greater flexion was found for the ‘grasp’ than for all remaining conditions.

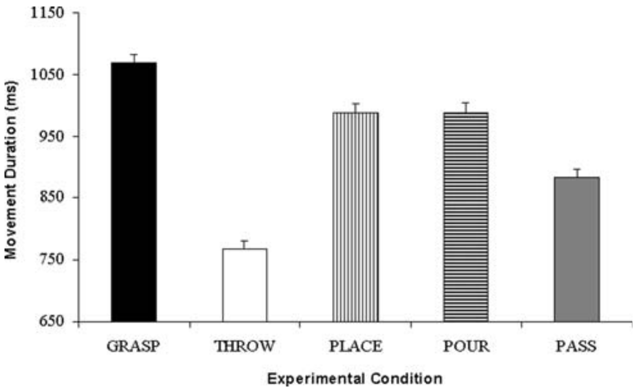

Fig. 2 Reach duration in milliseconds (ms) for the five experimental conditions. *Bars* represent standard error of the mean values

Differences depending on the type of subsequent actions were evident when comparing the ‘pour’ condition with the ‘place’, the ‘pass’ and the ‘throw’ conditions. As shown in Fig. 3, it is only after 60% of reach duration that the *pip* joints for both the middle and the ring fingers were more extended for the ‘pour’ than for the ‘place’, the ‘pass’, and the ‘throw’ conditions. During the first half of the movement the angular excursion of these joints did not significantly differ for the ‘pour’, the ‘place’, the ‘throw’, and the ‘pass’ conditions (see Fig. 3).

Abduction angles of adjacent digit pairs

Table 2 shows the results of the ANOVAs performed on the abduction angles for adjacent digit pairs. The interaction ‘Functional Goal’ by ‘Time’ was significant for the thumb–index, index–middle, middle–ring, and ring–little digits’ abduction angles. For these measures an effect of the presence/absence of a subsequent action was evident on the abduction angle between the thumb and the index finger. Specifically, from the beginning (i.e., 20%) up to the end of reach duration, the abduction angle between these two digits was larger for the ‘grasp’ than for the other conditions (see Fig. 4a).

A specific effect concerned with the type of subsequent action was evident for the index–middle and middle–ring fingers’ abduction angles. In particular, from 50% up to the end of reach duration (i.e., 90–100%), these angles were

Table 1 Results from the repeated measures ANOVAs performed on angular excursion for metacharpal-phalangeal (*mcp*) and proximal interphalangeal (*pip*) joints for all digits

Digits	Joints	Main factor of functional goal	Main factor of time	Interaction functional goal by time
Thumb	*mcp*	$F = 1.404_{(4,76)}$, NS	$F = 54.840_{(9,171)}$, $P < 0.0001$	$F = 5.128_{(36,684)}$, $P < 0.0001$
	pip	$F = 7.006_{(4,76)}$, $P < 0.0001$	$F = 49.289_{(9,171)}$, $P < 0.0001$	$F = 18.715_{(36,684)}$, $P < 0.0001$
Index	*mcp*	$F = 3.964_{(4,76)}$, $P < 0.007$	$F = 62.845_{(9,171)}$, $P < 0.0001$	$F = 11.785_{(36,684)}$, $P < 0.0001$
	pip	$F = 4.325_{(4,76)}$, $P < 0.004$	$F = 84.876_{(9,171)}$, $P < 0.0001$	$F = 18.829_{(36,684)}$, $P < 0.0001$
Middle	*mcp*	$F = 6.164_{(4,76)}$, $P < 0.0001$	$F = 64.179_{(9,171)}$, $P < 0.0001$	$F = 6.598_{(36,684)}$, $P < 0.0001$
	pip	$F = 3.425_{(4,76)}$, $P < 0.02$	$F = 51.464_{(9,171)}$, $P < 0.0001$	$F = 6.702_{(36,684)}$, $P < 0.0001$
Ring	*mcp*	$F = 4.841_{(4,76)}$, $P < 0.003$	$F = 63.073_{(9,171)}$, $P < 0.0001$	$F = 4.216_{(36,684)}$, $P < 0.0001$
	pip	$F = 11.109_{(4,76)}$, $P < 0.0001$	$F = 64.948_{(9,171)}$, $P < 0.0001$	$F = 6.751_{(36,684)}$, $P < 0.0001$
Little	*mcp*	$F = 7.129_{(4,76)}$, $P < 0.0001$	$F = 34.918_{(9,171)}$, $P < 0.0001$	$F = 5.603_{(36,684)}$, $P < 0.0001$
	pip	$F = 11.093_{(4,76)}$, $P < 0.0001$	$F = 47.915_{(9,171)}$, $P < 0.0001$	$F = 3.973_{(36,684)}$, $P < 0.0001$

NS not significant

larger for the 'throw' than for the other conditions (see Fig. 4b, c). On the contrary, these angles showed no differences across conditions from the beginning up to 40% of the reach duration (see Fig. 4b, c). Finally, no significant differences were found for the ring–little fingers' abduction angle depending on experimental conditions (see Fig. 4d).

Discussion

We set out to investigate whether grasping kinematics are sensitive to both the presence and the type of action following a reach-to-grasp movement toward the same object. Results indicate that temporal and angular aspects of performance are strongly modulated by the purposive component driving the action. These findings extend current grasping literature in two important ways. First, in contrast to previous research which has mainly focused on grasping *per se*—a quite atypical behavior, given that grasping is normally followed by some other actions—we designed a series of tasks which allow to specifically investigate the effects of end-goal on the planning and execution of reach-to-grasp movements along different dimensions. Second, rather than limiting our analysis to thumb–index finger separation, which may provide a limited amount of information, we considered kinematics at the level of individual finger joints.

The effect due to the presence of an action following grasping

When there was no action beyond grasping, reach duration was longer than when the closing of the fingers upon the object represented the starting point for a subsequent action. This result is in agreement with previous evidence suggesting that when the goal of a reach-to-grasp movement encapsulates a subsequent action, the duration of the 'first' movement is shorter than when no subsequent action is requested (e.g., Ansuini et al. 2006; Gentilucci et al. 1997). A possible explanation for this effect might be found in the relationship between the time course of the deceleration phase and the online integration of sensory feedback. For instance, it has been shown that when an actor intends to grasp an object and no transportation movements are requested thereafter, reach duration is longer with respect to the condition in which transportation movements are requested (Johnson-Frey et al. 2004). Therefore it might well be that reach duration is longer for the 'grasp' condition because the movement necessary to achieve the intended goal (i.e., grasping) is not specified by the dynamic constraints of the task, causing subject to rely more heavily on sensory feedback.

With respect to hand posture during reaching, the beginning of opening and closing phases was earlier for the 'grasp' condition than for the other conditions. This time shift may signify that the end-point is taken into account: when no subsequent action is requested the end-point location is nearer than when a subsequent action has to be performed. In this respect, many reach-to-grasp studies have consistently reported that parameters concerned with the grasp component are sensitive to object distance (e.g., Gentilucci et al. 1991; Jakobson and Goodale 1991). For instance, the time of maximum grip aperture is brought forward for farther objects (Jakobson and Goodale 1991). Although in the present study object distance was not varied, it might be hypothesized that when planning kinematic parameterization, it is the end-point 'distance' rather than the object distance which may be taken into account.

An effect on the thumb–index finger abduction angle was also revealed. This angle was greater for the 'grasp' than for the other conditions. The absence of a subsequent action implies that no or little force production is needed as to

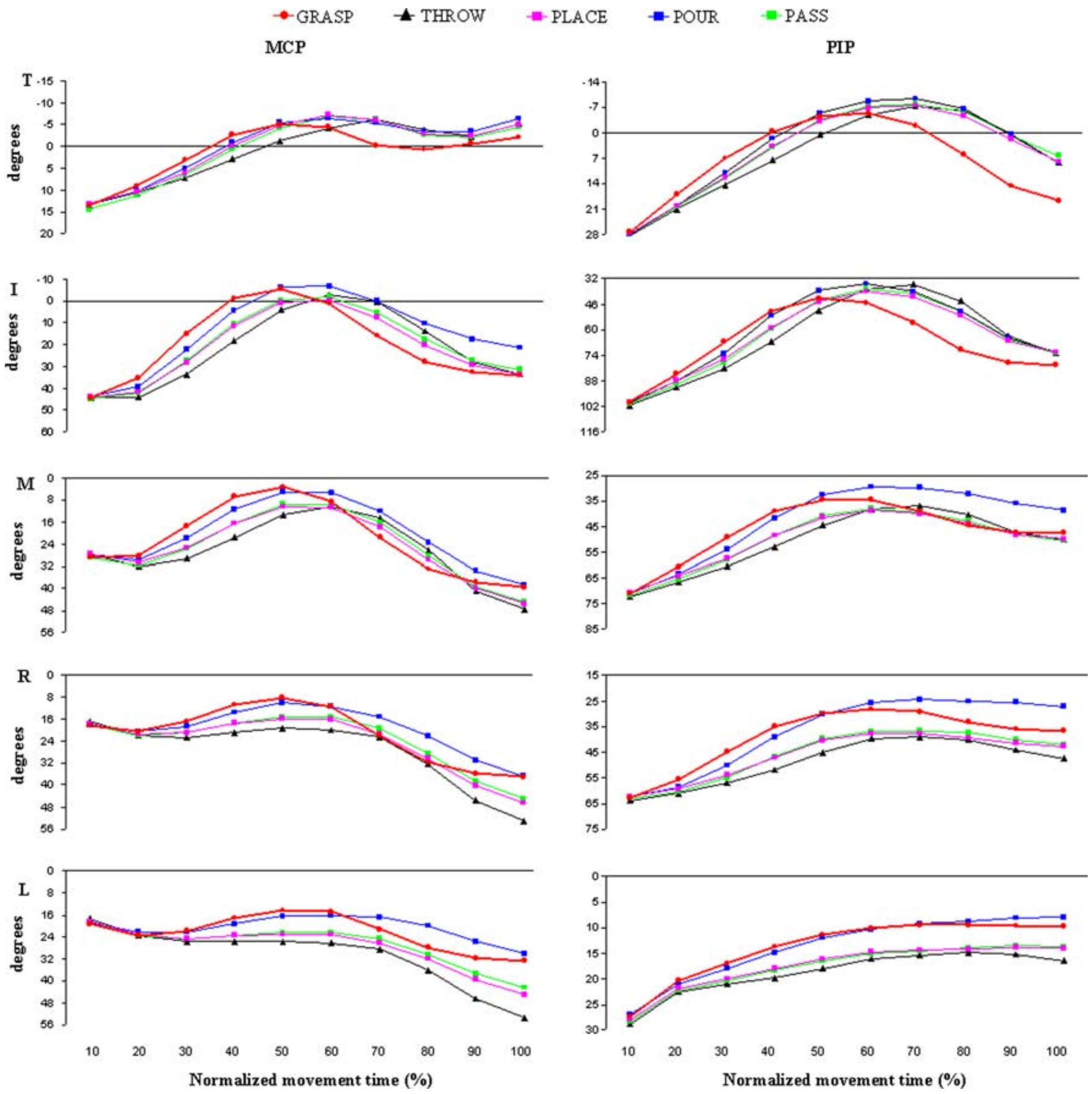

Fig. 3 Each trace depicts angular excursion of both *mcp* and *pip* joints (*left* and *right* columns, respectively) of thumb (*T*), index (*I*), middle (*M*), ring (*R*), and little (*L*) finger for all experimental conditions. Data are averaged across trials and subjects

Table 2 Results from the repeated measures ANOVAs performed on angular distances between adjacent digits

Fingers' angular distances	Main factor of functional goal	Main factor of time	Interaction functional goal by time
Thumb–index	$F = 7.148_{(4,76)}$, $P < 0.0001$	$F = 45.575_{(9,171)}$, $P < 0.0001$	$F = 3.255_{(36,684)}$, $P < 0.0001$
Index–middle	$F = 2.202_{(4,76)}$, NS	$F = 2.100_{(9,171)}$, $P < 0.04$	$F = 2.499_{(36,684)}$, $P < 0.0001$
Middle–ring	$F = 4.448_{(4,76)}$, $P < 0.004$	$F = 21.747_{(9,171)}$, $P < 0.0001$	$F = 5.574_{(36,684)}$, $P < 0.0001$
Ring–little	$F = 1.438_{(4,76)}$, NS	$F = 15.835_{(9,171)}$, $P < 0.0001$	$F = 2.878_{(36,684)}$, $P < 0.0001$

NS not significant

counteract the tangential pull of gravity during the lifting of an object. Since the thumb and index finger have a larger force production capability than the other digits (Kinoshita et al. 1995), these two digits and their contact points on the object might have been functionally less important (and therefore planned more liberally) when no subsequent action was requested. Support for this hypothesis comes from recent findings indicating that the spatial distribution of digit contact points on the to-be-grasped object is modulated according to the force requirements being implicit in

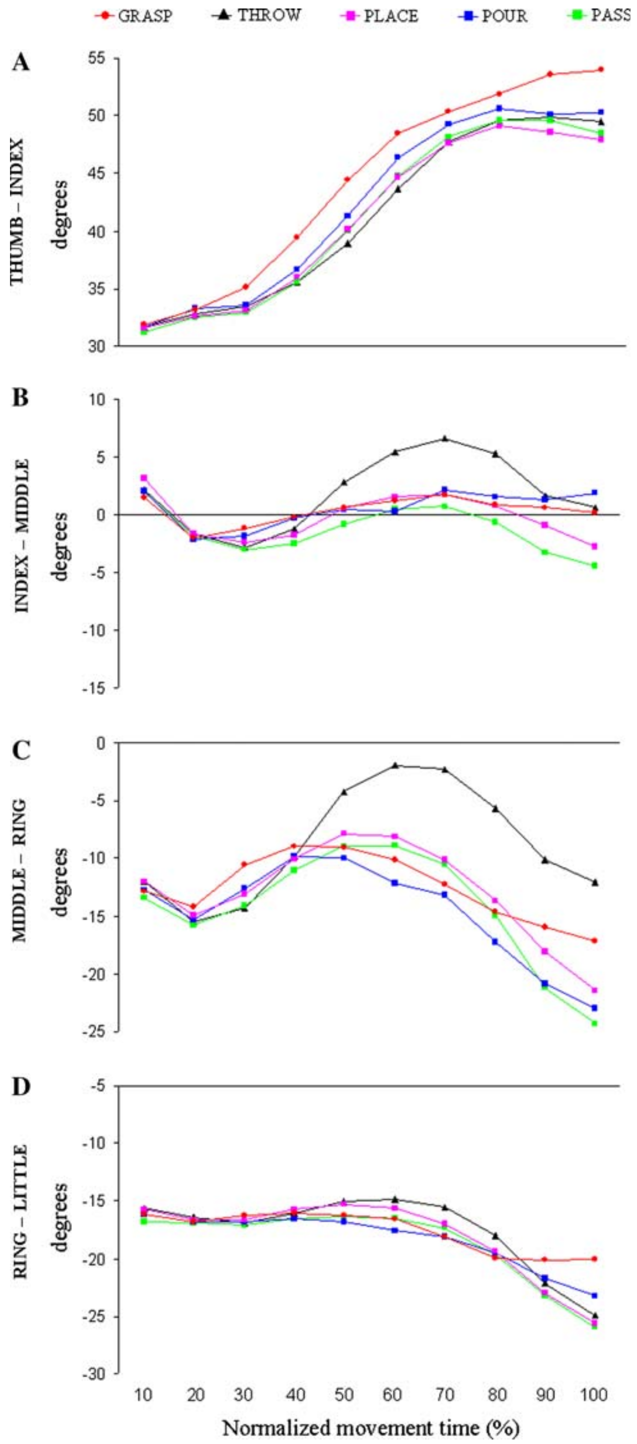

Fig. 4 The time course of angular distance between thumb-index (*Panel A*), index-middle (*Panel B*), middle-ring (*Panel C*), and ring-little fingers (*Panel D*), respectively, for each experimental condition. Data are averaged across trials and subjects

the manipulation following object grasp (Lukos et al. 2007).

An alternative account which may explain the differences in kinematics for the conditions involving a subsequent action with respect to the 'grasp' condition is concerned with the direction of gaze during these trials.[1] Human gaze behavior has been studied in various dynamic activities, including natural manipulation (Land et al. 1999; Smeets et al. 1996; Johansson et al. 2001). For instance, Johansson et al. (2001) investigated where subjects direct their gaze in a natural manipulation task in which they grasped and moved a bar to a target and then returned the bar to the support surface. Subjects directed gaze almost exclusively toward objects involved in the task. Furthermore, subjects fixated certain landmarks associated with these objects. Importantly, it appeared that gaze marked key positions to which the fingertips on grasped objects were subsequently directed (actual and potential contact points). Thus, the salience of potential gaze targets was largely determined by the demands of the sensorimotor task. Although we were unable to monitor gaze direction during the present tasks, it might well be that for the 'grasp' condition gaze worked less selectively in anchoring thumb and index finger contact points whose determination would have been more important for the conditions which imply object transportation.

The effect of the type of action following grasping

What is to occur beyond the grasping of an object did have a specific effect on reach duration. In particular, the progressive shortening of reach duration for the 'pour', 'place', 'pass', and 'throw' conditions, respectively, may reflect the degree of accuracy associated with the action goal. In this respect, it is well-known that reach duration increases when accuracy increases (Fitts 1954; Bootsma et al. 1994). Although this effect has been classically demonstrated by varying object size, it has also been noticed by varying the accuracy constraints related to the action end-goal. This explanation is consistent with previous findings showing that reach duration was longer when the same object, once grasped, had to be fit in a similar sized opening rather than thrown within a larger container (Marteniuk et al. 1987).

When considering fingers' angular excursion, both the middle and the ring fingers were more extended when the bottle was grasped for pouring than to accomplish the other goals considered here. This result might reflect the need to balance the counterclockwise external torque dictated by the wrist rotation component embedded in the pouring action. To do so, some digits will generate antagonist moments (i.e., assisting the external torque) and some others will generate agonist moments (i.e., resisting to the external torque) (Gao et al. 2006). According to the definition provided by Zatsiorsky et al. (2003), the agonist

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[1] We thank an anonymous reviewer for suggesting this alternative explanation.

moment would be supplied by the "peripheral" fingers (i.e., index and little fingers) and the antagonist moments by the "central" fingers (i.e., middle and ring fingers). In this perspective the bigger extension of the middle and the ring fingers (i.e., "central finger" fingers) found in the present study might represent the kinematic anticipation of this forward dynamic need.

Finally both the index–middle and the middle–ring abduction angles were larger for the 'throw' than for the other conditions. For the throwing action, bigger distances for index–middle and middle–ring abduction angles might be either an index of low accuracy or the need to exert more force as throwing may require. Altogether, these findings indicate that the central nervous system (CNS) stipulates sensorimotor programs that specify both the required fingertip actions and the expected sensorimotor consequences associated with different end-goals. The development of such differential sensorimotor programs dependent upon end-goals supports predictive, anticipatory motor control mechanisms in manipulation as outlined below.

Anticipatory control of motor sequences

The ability to predict the consequences of our own actions relies on the use of internal models. Internal models are neural mechanisms that can mimic the input/output characteristics, or their inverse, of the motor apparatus (Kawato 1999). Internal models by which the CNS represents the causal relationship between actions and their consequences (i.e., motor-to-sensory transformation) are called forward models. Internal models by which the CNS implements the transformation from the desired consequences to actions (i.e., sensory-to-motor transformation) are called inverse models (Wolpert and Ghahramani 2000). As the inverse internal models can provide the motor command to achieve some desired state transition, they are well suited to act as controllers (Wolpert and Kawato 1998). Within this theoretical framework, a modular structure has been proposed in which multiple inverse models exist to control the system and each one is paired with a corresponding forward model. Each paired forward and inverse model forms a module together with a responsibility predictor (RP). The RP allows the system to switch between modules prior to generation of a motor command and evaluation of its consequences. The RP switches between modules on the basis of contextual information that could be (among other things) a sequence of movement elements (Kawato 1999). The RP concept might be useful in explaining the present results. That is, the RP may provide an *a priori* probability for the selection of a unique module which corresponds to the goal of the actions used here or to two modules, one for the reach-to-grasp action and one for the subsequent action. Although both proposals may provide a suitable explanation for the present results, we are tempted to suggest that the 'two modules' hypothesis may better fit the present data. This is because it might well be that multiple internal models can be mixed in an adaptive way when necessary and when dealing with an environment in which both transformation are present (Ghahramani and Wolpert 1997; Flanagan et al. 1999). To translate this theoretical framework within the context of our experiment it might well be that the CNS may combine internal models relative to the sensorimotor transformations characterizing the two steps of the action (i.e., reach-to-grasp and the task following it) considered here – one concerned with the reach-to-grasp movement, the other concerned with the subsequent action. Importantly such an ability of the motor system to integrate different modules would make it able to generate a vast repertoire of motor behaviors by mixing the outputs from the different modules such that the final output reflects the relative and weighted contribution of each one for the attainment of the overarching goals guiding action.

Conclusions

A fundamental issue that any model of grasping should consider is that objects can be grasped differently depending on the goal and intentions of the grasping agent. Although a few studies have investigated how intended actions influence the planning and execution of manipulative actions, these studies have paid little attention to differences in the shape assumed by individual fingers when performing grasping movements to the same object for different purposes. In all cases, only the maximum distance between index finger and thumb was measured. Therefore, such studies might not provide definitive tests of the extent to which different types of manipulative patterns are used depending on action end-goals. Rather, the present study provides an original attempt to shed some light on how the motions of individual finger joints toward an object vary according to the intent of what we wish to do with that object following its grasp. The demonstration of the influence of different after-grasp movements on the kinematics of the preceding prehension movement emphasizes the importance of predictive motor control mechanisms in motor control.

Acknowledgments We would like to thank Federico Tubaldi for his comment on an earlier version of the manuscript and Stefano Massaccesi for his technical support. This work was supported by a research grant from the Italian Ministry of Research (MUR) to UC.

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