Changes in grasping kinematics due to different start postures of the hand
Constanze Hesse, Heiner Deubel

To cite this version:
Constanze Hesse, Heiner Deubel. Changes in grasping kinematics due to different start postures of the hand. Human Movement Science, Elsevier, 2009, 28 (4), pp.415. <10.1016/j.humov.2009.03.001>. <hal-00557315>

HAL Id: hal-00557315
https://hal.archives-ouvertes.fr/hal-00557315
Submitted on 19 Jan 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Accepted Manuscript

Changes in grasping kinematics due to different start postures of the hand

Constanze Hesse, Heiner Deubel

PII: S0167-9457(09)0035-9
DOI: 10.1016/j.humov.2009.03.001
Reference: HUMOV 1144

To appear in: Human Movement Science

Received Date: 20 November 2008
Revised Date: 2 March 2009
Accepted Date: 5 March 2009

Please cite this article as: Hesse, C., Deubel, H., Changes in grasping kinematics due to different start postures of the hand, Human Movement Science (2009), doi: 10.1016/j.humov.2009.03.001

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Changes in grasping kinematics due to different start postures of the hand.
Constanze Hesse & Heiner Deubel

RUNNING HEAD: "Grasping with different start postures"
keywords: grasping, perturbation, posture, kinematics, motor control

Correspondence should be addressed to:
Dr. Constanze Hesse
Ludwig-Maximilians-Universität München
Department of Experimental Psychology
Leopoldstr. 13
80802 München, Germany
Phone: ++49 (0)89 2180 6229
Fax: +49(0)89 2180 5211
Email: constanze.hesse@psy.lmu.de

Abstract

It was proposed that grasping is a relatively stereotyped movement pattern which can be subdivided into the components of manipulation, transport and orientation of the hand. However, it is still a matter of debate whether these components are independent of each other. In three experiments we altered the start posture of the hand by either changing the size of the start aperture or the orientation of the hand prior to movement onset. The variation of the aperture size primarily affected the manipulation component of the grip resulting in an overall change of the pre–shaping profile. In contrast, an alteration of the start orientation affected the manipulation and the transport components to a similar extent. These results give further evidence that hand orientation is neither planned nor controlled independently from the other movement components. Moreover, when the grip had to match specific object properties, adjustments were mainly achieved within the first movement part. In contrast, when there were no movement constraints the final finger
positions were influenced by the initial start posture of the hand. We found no evidence for a fixed spatial or temporal coupling of the grasp and the transport component in our experiments.

Introduction

During reach-to-grasp movements, fingers open gradually until they reach a maximum (larger than the actual size of the object), followed by a gradual closure of the grip until it matches the object’s size (Jeannerod, 1981, 1984). Maximum grip aperture (MGA) has thereby turned out to be the most prominent kinematic landmark that is sensitive to most changes in task demands like variations in object size (e.g., Jeannerod, 1981, Marteniuk, Leavitt, MacKenzie, & Athenes, 1990), object shape (e.g., Gentilucci et al., 1991, Zaal & Bootsma, 1993), and object weight (e.g., Weir, MacKenzie, Marteniuk, and Cargoe, 1991, Johansson and Westling, 1988, Gordon, Forssberg, Johansson, and Westling, 1991; for review see Smeets and Brenner, 1999). Moreover, the grasp component is not only influenced by the physical dimensions of an object but also by dynamic aspects and accuracy constraints of the movement (Wing, Turton, & Fraser, 1986, Zaal & Bootsma, 1993). Although movement parameters vary depending on the requirements of the grasping task the general pre-shaping of the hand remains a highly stereotyped motor pattern.

Jeannerod (1984) was among the first to formally describe grasping behavior. He postulated that grasping consists of two components: the transport component which carries the hand to the location of the object (proximal component) and the grasp component which shapes the hand in anticipation of the grip (distal component). Since MGA is mostly reached at about two thirds of the movement duration, Jeannerod (1984) stated that both components work independently but are temporally coupled. This classical description of grasping is still rather influential and many models have been centered around the precise nature of this coupling by proposing several timing mechanisms (e.g., Bootsma & van Wieringen, 1992, Hoff & Arbib, 1993, Hu, Osu, Okada, Goodale, & Kawato, 2005). Besides these models being founded on the concept of temporal coupling of transport and grasp, there are other models that suggest that transport and grasp are spatially coupled (e.g., Haggard & Wing, 1998, Alberts, Saling, & Stelmach, 2002, Rand & Stelmach, 2005). The main idea of these models is that the distance traveled by the wrist after MGA (aperture closure distance) remains relatively invariant under different task constraints.

The assumption that there are two different visuo–motor channels working in parallel without sharing information, however, has also been challenged by perturbation studies. If the object position related to the transport component and/or the object size related to the manipulation component were perturbed at the beginning of the grasping movement, there were also changes observed in the component which was not directly affected by the perturbation (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991, Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991, Castiello, Bennett, & Chambers, 1998, Bennett & Castiello, 1995). Furthermore, this very influential view on grasping was also questioned by Smeets and Brenner (1999), who proposed an alternative model which assumes that the final finger position is the only controlled variable in prehension. This model, which describes the movement of the fingers using the minimum jerk approach predicts most of the experimental results in grasping accurately, without sub–dividing grasping into two components (reviewed in Smeets & Brenner, 1999). Apart from
perturbation studies which changed object size and/or object position once the movement started, there are only a few studies which altered the grip prior to movement onset (Wallace, Weeks, & Kelso, 1990, Saling, Mescheriakov, Molokanova, Stelmach, & Berger, 1996, Timmann, Stelmach, & Bloedel, 1996a). In these studies participants had to start their grasping movements with their fingers initially stretched. Results showed that the grasp component "reorganized" itself during the first part of the movement while the transport component remained relatively unaltered (Timmann, Stelmach, & Bloedel, 1996b, Saling et al., 1996). Interestingly, the variation of the aperture size prior to movement onset resulted in considerable changes of the stereotyped pre-shaping profile. Instead of closing the fingers progressively in order to match the object size (which would result in the loss of a MGA) it was shown that in most trials participants began to close their fingers during the first phase of the wrist transport and then re-opened them prior to object grasp (Saling et al., 1996, Timmann et al., 1996a). However, in the study of Wallace et al. (1990) the paradoxical closing and reopening pattern was not observed. It was argued by Timmann et al. (1996a) that the reopening of the grip might occur only if the difference between initial opening aperture and object size is large enough.

In this study we want to investigate this issue more systematically by varying the size of the starting aperture as well as object size. So far, very little attention has been paid to the effects of varying the starting posture of the hand on grasping kinematics although in everyday life we rarely start grasping with the hand aligned to the body midline and all fingers pinched together, as done in most grasping studies. Thus, this study adds to the understanding of human grasping in more complex and natural situations.

In addition to the shaping of the hand due to object size, the fingers have to be oriented according to the orientation of the object to achieve a stable grip. A particular feature of adjusting the hand orientation to the object is that this process affects the grip as well as the transport component of the movement. It was proposed that object and hand orientations constitute a third component which integrates reaching and grasping components (Soechting & Flanders, 1993, Stelmach, Castiello, & Jeannerod, 1994, Gentilucci, Daprati, Gangitano, Saetti, & Toni, 1996). According to the "schema theory of grasping" by Iberall and Arbib (1990) the two main parameters for planning a grasp are the finger aperture and "finger opposition axis" which have to be tuned to the dimensions of the object. The authors suggest that most hand postures can be described very well by these two parameters alone. Compared to grasping studies investigating the effects of object size and object position on grasping kinematics, there are very few studies that examine the role of object and hand orientation while grasping objects (Jeannerod & Decety, 1990, Stelmach et al., 1994, Gentilucci et al., 1996, Desmurget et al., 1996, Mamassian, 1997, Cuijpers, Smeets, & Brenner, 2004). In these studies the orientation of the target which participants had to grasp or to which participants had to adjust their fingers, was varied.

While the variation of aperture size before movement onset has previously been explored, we are not aware of any study that varied the orientation of the hand/fingers prior to movement start (although there are some studies varying the position of the hand relative to the target object, e.g. Roby-Brami, Bennis, Mokhtari, and Baraduc, 2000, Bennis and Roby-Brami, 2002). Again we would argue that starting the grasping movement with different hand and finger orientations reflects a common situation in everyday life.

The aim of this study is to examine the changes in grasping kinematics resulting from a change of the starting posture of the hand. We are especially interested in the way in
which and over what time course the grip is adjusted to the object’s properties. Furthermore, we want to investigate how the different components of the movement (transport and grasp) are affected and whether their temporal and/or spatial coupling persists if the initial start posture is changed. In the first experiment we varied the size of the starting aperture systematically. Participants had to grasp objects of different sizes starting with the fingers pinched together (closed aperture), slightly open, widely open, or fully stretched. In a second experiment we varied the orientation of the grip at movement beginning and participants had to grasp a cylinder which was presented at different positions. This was done because several studies have reported that the grip orientation depends on the movement direction (e.g., Paulignan, Frak, Toni, & Jeannerod, 1997, Roby-Brami et al., 2000). In the third experiment we used the same starting orientations of the grip but this time the orientation of the object to grasp was also changed such that participants had to orient their hands very precisely in order to grasp the object successfully.

Experiment 1

Methods

Participants

Ten undergraduate and graduate students of the Ludwig–Maximilians–University Munich (five male, five female; mean age = 28, SD = 5) participated in the experiment. They were paid 8 Euro per hour of participation. All participants were right–handed by self report, had normal or corrected-to-normal visual acuity, and were naive with respect to the purpose of the study.

Apparatus and stimuli

Participants sat comfortably on an adjustable chair within a lit room. A chin rest was used to maintain a constant head position throughout the experiment. They looked at a wooden board (72 x 50 cm) which was placed on the tabletop and served as presentation surface for the stimuli. Three cylindrical objects made of wood served as the target stimuli. All objects had a circular base (diameter of the small object 2.5 cm, diameter of the medium sized object 4.0 cm, and diameter of the large object 5.5 cm) and a height of 5.5 cm. Objects were always presented at the same position marked with a pin upon which each object was affixed.

Trajectories of the grasping movements were recorded using a Polhemus Liberty electromagnetic motion tracking system at a sampling rate of 240 Hz. Polhemus sensors were attached to the nails of the thumb, and the index finger of the right hand (using adhesive pastels: UHU-patafix, UHU GmbH, Bühl, Germany and medical tape). An additional sensor was attached to the back of the hand (wrist sensor).

Procedure

Participants began each trial with the index finger and thumb of the dominant right hand located at the starting position (marked by a pin). The exact placement of the fingers depended on the starting conditions which are described in the text that follows. The
distance between starting position and object was about 30 cm. Between all trials participants were asked to keep their eyes closed. This allowed the experimenter to place the target object on the table without being watched by the participant. In addition, participants wore headphones through which different tones were presented: The first tone signalled them to close their eyes so that the experimenter could prepare a new trial by placing the object, the second tone signalled that the participants should open their eyes and to look at the object, after this preview period which lasted one second, a third tone indicated to them that they should start the grasping movement. In response to the third auditory signal, participants grasped the cylinder, lifted it, placed it halfway between object and starting position on the table, and moved their hand back to the starting position. After three seconds participants heard the first tone again which indicated that they should close their eyes. Subsequently, the experimenter returned the cylinder and prepared the next trial. No instructions were given as to speed of initiation and the speed of the movement.

There were four different conditions varying the size of the starting aperture. In the "pinched together" grip condition (PG-condition) participants began their movement with both fingers closed around the starting position. In the "small grip aperture" condition (SG-condition) participants closed the fingers around a disk which had the same diameter as the small object to grasp (2.5 cm) and a height of 1.0 cm. The object was attached centrally at the starting position. In the "large grip aperture" condition (LG-condition) participants had to grasp a disk with the same diameter as the large object (5.5 cm and 1.0 cm in height) with index finger and thumb before each trial. Finally, in the fourth condition, participants had to stretch their fingers such that the distance between index and thumb was maximal ("fully stretched" grip condition (FG-condition)). While the hand was fully stretched the starting position was located halfway between index and thumb in the interdigital space.

In all conditions participants were allowed 3 s to execute the movement. If this time limit was exceeded, the trial was classified as an error and repeated later in the experiment at a random moment. The different starting conditions were presented in blocks of 30 trials (10 trials per object size) with three practice trials preceding each condition. The order of blocks was counterbalanced across participants and the sequence of presentation within each condition was in pseudo random order.

**Data Processing**

The finger trajectories were filtered off-line using a second-order Butterworth Filter that employed a low-pass cut–off frequency of 15 Hz. Movement onset was defined by a velocity criterion. The first frame in which the wrist exceeded a velocity threshold of 0.1 m/s was taken as movement onset. Reaction time (RT) was defined as the time between the auditory signal and movement onset. The first frame in which the velocity of the wrist dropped below a threshold of 0.1 m/s was taken as the touch of the object. Movement time (MT) was defined as the time between movement onset and touch of the object.

Furthermore, the aperture profile (3D distance between the two sensors on index finger and thumb) was determined. Since it was proposed that starting a grasping movement with open fingers leads to a closing and reopening pattern in the aperture profile, we searched for local minima and local maxima in the aperture profiles (Saling et al., 1996, Timmann et al., 1996a). Therefore, we differentiated the aperture profile for each participant and each trial until the object was touched. Whenever there was a change
in the algebraic sign from minus to plus in the velocity trace, a local minimum was detected indicating a "dip" in the aperture profile. Correspondingly, a subsequent change in the algebraic sign from plus to minus indicated a second maximum. The last maximum of this analysis was defined as maximum grip aperture (MGA) for all conditions. When there was only a single peak in the aperture profile, this peak was taken as MGA.

To characterize the transport component of the grasping movement we calculated the midpoint between index and thumb. We determined the amplitude of peak velocity (APV), time to peak velocity (TPV), the amplitude of peak deceleration (APD) and the time to peak deceleration (TPD) from this measure by differentiation of the position signal. Movement trajectories were quantified after time normalization of the data. The mean and the standard deviations of the mean X and Y positions of each sensor were calculated for each of the 100 normalized frames.

The coupling of the grasp and the transport component under different start aperture conditions was examined using a temporal and a spatial measure: To determine the occurrence of MGA temporally, the normalized aperture opening time expressed as percentage of MT, was calculated. Secondly, as a more accurate measure we correlated the relative time to MGA with the relative TPD of the wrist. For a spatial measure, we calculated the distance traveled until MGA occurred and the distance traveled from MGA to the touch of the object (c.f. Rand, Squire, & Stelmach, 2006). These distances were calculated as the cumulative resultant trajectory lengths (in x and y) between two positions of the thumb sensor. We decided to use the thumb sensor and not the wrist sensor to compute trajectory length since it was argued by Haggard and Wing (1997) that the motor system is more concerned with thumb position than with wrist position during hand transport.

Data were analyzed using repeated measures analysis of variance (ANOVA) and the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959). This corrects for possible violations of the sphericity assumption in repeated measures data resulting in a more conservative testing. Values are presented as means ± standard errors of the mean. Post-hoc contrasts were carried out using Fisher’s LSD (least significant difference) testing procedure. If not stated otherwise, a significance level of $\alpha=.05$ was used for the statistical analyses.

Results

Kinematics of the grip component

MGA and aperture profiles: We examined the changes in the aperture profile due to different sizes of the starting aperture of the hand. The most prominent landmark of the kinematic profile is therefore the MGA. Figure 1 shows the mean size of the start aperture in different conditions and the corresponding MGAs. The MGA was of similar size in all conditions and, as expected, was influenced by object size. That the MGA was overall a bit larger in the FG– conditions can be explained by the fact that when there was no second (late) peak in the aperture profile, the MGA was determined as the first peak which occurred shortly after movement onset. (Note, that in the trials in which MGA occurred simultaneously with the movement onset, no MGA was determined.)

Insert Figure 1 about here
As discussed above, studies introducing an altered aperture at movement beginning reported a pattern of aperture closing and reopening instead of a smooth closing of the fingers (e.g., Saling et al., 1996, Timmann et al., 1996a). Here we examined the occurrence of a local minimum ("dips" which indicates an initial aperture closing) in the aperture profile in a systematical way (see also Hesse & Franz, 2008). Figure 2 shows the percentage of movements with a "dip" averaged over all participants for the different start aperture conditions. The repeated–measures ANOVA revealed no effect of object size, \( F(2,18)=1.1, p=0.34 \), but a significant effect of start aperture \( F(3,27)=13.2, p=0.001 \). Post–hoc tests indicate that there were significantly fewer "dips" when participants began their grasp with all fingers pinched together compared to all other conditions (all \( p<0.008 \)). No interaction effect was found \( (p=.17) \). In Figure 3 representative single subject trials are depicted for the different conditions. The finding that there are approximately 20–30% of "dips" in the pinched together conditions is consistent with our recent results on the occurrence of double–peaks during normal grasping (Hesse & Franz, 2008), since the occurrence of a secondary peak in the aperture profile always corresponds with the occurrence of a local minimum.

To investigate the changes in the grip over time in further detail we also calculated the mean aperture profiles over all participants. For this purpose, we time–normalized each movement from its onset until the touch of the object, and calculated the size of the aperture every 5% of the movement time. As seen in Figure 4 the aperture profile in all four conditions gets similar shortly before MGA or before the second peak is reached. Thus, the closing–phase remains alike over all conditions. This implies that the variation of the start aperture size only affects the first half of the movement. The mean trajectories of the fingers and the wrist for the different conditions are depicted in Figure 5.

### Kinematics of the transport component

**RT and MT:** RT and MT were neither influenced by the size of the starting aperture nor by the changes of object size (all \( p>0.34 \)). On average it took participants 293\( ms \pm 6ms \) to initiate and 699\( ms \pm 27ms \) to complete the grasping movement.

**Velocity and deceleration:** It was often observed that wrist movements in a standard grasping task have a single peak and a bell–shaped velocity profile. Thus, they can be
well characterized by measuring the amplitude and the (relative) timing of peak velocity and peak deceleration (e.g., Paulignan, MacKenzie, et al., 1991, Paulignan, Jeannerod, et al., 1991). Figure 6 shows the mean values of all wrist parameters. A 4 (start aperture size) x 3 (object size) repeated measures ANOVA applied on the data revealed that the object size as well as the start aperture size had no effect on any of the wrist parameters measured (see Table 1).

Insert Table 1 about here

Insert Figure 6 about here

Coupling

Timmann et al. (1996a) reported that in 60% of all trials in which participants started their grasping movement with the fingers apart the wrist velocity profile also showed an inflection (additional peak). They supposed that this second peak might indicate that transport and grasp component are planned together. We looked for an additional inflection of the wrist velocity profile in the same way as for the aperture profile, by searching for local maxima. Overall, we found fewer secondary peaks in the wrist velocity profile than Timmann et al. (1996a): 11.4%±3.9% in the PG– condition (which can be considered as baseline), 15.3%±4.0% in the SG– condition, 15.0%±5.3% in the LG– condition, and 28.2%±8.6% in the FG condition. Therefore, data indicated only a tendency for slightly more additional peaks in the FG– condition, \(F(3,27)=3.2, p=.08\).

Spatial and temporal coupling: As discussed in the introduction there are different theories suggesting a spatial (e.g., Haggard & Wing, 1998, Alberts et al., 2002, Rand & Stelmach, 2005) versus a temporal coupling (e.g., Jeannerod, 1984, Paulignan, MacKenzie, et al., 1991, Hoff & Arbib, 1993) of the grasp and transport components. In this study we wanted to test if there is a fixed spatial or temporal coupling if the size of the start aperture is varied. In Figure 6f, the distances traveled by the thumb from movement onset to the occurrence of MGA and from MGA to the touch of the object are shown for the different start aperture conditions. It was proposed that the distance which has to be covered by the hand after MGA, remains relatively stable under different movement conditions (e.g., Alberts et al., 2002, Rand & Stelmach, 2005, Rand et al., 2006). Figure 6f shows that the distance traveled after MGA until the touch of the object is much longer in the FG– conditions (11.0 cm±2.5 cm), whereas it was of similar length in all other conditions, PG–conditions (3.7 cm±0.5 cm), SG–conditions (3.1 cm±0.6 cm) and LG–conditions (4.0 cm±0.8 cm). The larger distances in the FG–conditions result most likely from the trials in which participants show an early first peak and no second late peak in the aperture profile. Additionally, we found a significant effect of object size on the aperture closure distance, \(F(2,18)=9.3, p=.004\). Post–hoc tests indicate, that participants start to close their fingers earlier when grasping smaller objects (all \(p<.04\)).

A rough measure of the temporal coupling of the grasp and the transport is the occurrence of MGA within MT, which was supposed to be relatively fixed (Jeannerod, 1984; for review see, Smeets and Brenner, 1999). Therefore, we further examined the effect of the different start aperture sizes on the aperture opening time expressed as percentage of MT. Figure 6e shows that the MGA in the FG–conditions (57%±7%) was
reached earlier in MT than in all the other conditions (79±2% in the PG– conditions, 81±2% in the SG– conditions, and 77±2% in the LG– conditions). Furthermore, we observed a significant effect of object size which indicates that the MGA occurs later in MT when the object size increases, \( F(2,18)=15.4, p<.001 \). The interaction between object size and size of the start aperture also became significant, \( F(6,54)=2.7, p=.05 \). Since many studies have shown that the relative timing of MGA varies with task demands, one could argue that the occurrence of MGA within the MT might be a too simplistic measure to detect the temporal coordination of grip and transport. Hence, we also correlated the relative time to MGA with the relative TPD of the transport component, which is supposed to be a more robust measure of temporal coupling. However, none of these correlations were found to be significant. This implies that both components were not strictly temporally coupled.

**Discussion**

In this experiment, we disturbed the well known biphasic grip pattern consisting of an opening of the fingers until the MGA, and the subsequent closing until the object is touched, by varying the size of the aperture openings before movement onset. Our findings confirm the observation that the grip formation is altered during the first half of the movement whereas the second half of the movement remains relatively unchanged. The grip formation, when beginning the movement with the fingers apart, is mainly characterized by an initial closure of the grip resulting in a dip in the aperture profile (Timmann et al., 1996a, Saling et al., 1996). By using different start aperture sizes as well as different object sizes, we could show that the initial closing of the aperture does not only occur when the fingers are fully extended but equally often when the aperture is only slightly open at movement onset. We found no evidence for the proposition that the closing and re–opening of the aperture only occurs if the difference between the aperture size and the object size is very large, as suggested by Timmann et al. (1996a).

Additionally, in the SG–condition participants had to open their fingers wider in order to grasp the object successfully whereas in the FG–conditions the fingers had to close only. Despite this difference, the closing and reopening pattern was found in both conditions. Interestingly, it was already pointed out by Smeets and Brenner (2002) that neither their model on digit control (Smeets & Brenner, 1999) nor the more complex posture model of Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) can correctly predict the alterations of the grip profile due to different start aperture sizes.

However, there is another possible explanation for the occurrence of the first peak and the subsequent closing ("dip") in the aperture profile in the SG and LG–conditions (cf. Figure 3). In these conditions, participants hold a real object (the start disc) between their fingers at movement onset. Thus, the first part of the aperture profile could also represent the release of the start object. In that case the change in the profile would indicate the superposition of two sub–movements: releasing the first object and grasping the second object. In a pilot study we checked for this simple explanation: five participants (which also participated in Experiment 1) repeated the SG and LG–conditions without holding a real object between their fingers. The size of the start aperture was marked on the presentation board and corresponded to the size of the starting discs used in the SG–conditions and LG–conditions, respectively. Using these conditions we still found an increased percentage of local minima compared to the PG–conditions: 51±7% for the
SG–conditions and 67%±10% for the LG–conditions. Overall, we observed that the initial closing persisted while the initial peak (prior to the dip) became less pronounced when no object was held prior to movement onset. The fact that there is an initial closing of the aperture is also consistent with our observation of the aperture closing and re–opening in the FG–conditions since in these conditions no object was held between the fingers.

Concerning the transport component of the grasping movement, we were able to replicate the finding that the variations of the start aperture did not affect the main kinematic landmarks (Timmann et al., 1996a, Saling et al., 1996). The grip was executed equally fast in all conditions. This finding suggests that all start apertures are treated as equally likely by the motor system. In other words, no additional on–line correction is required when participants start grasping with the fingers apart. Furthermore, we found no evidence for an additional inflection in the wrist velocity profile at the time the fingers start to reopen as observed by Timmann et al. (1996a). However, Timmann et al. (1996a) proposed themselves that the additional inflection in the wrist velocity profile found in their data might be due to the slowness of the movement resulting in discontinuities in the wrist velocity profile (see also Milner, 1992).

Finally, we questioned how the occurrence of MGA was affected temporally and spatially by a change of start aperture size. The data revealed a surprisingly consistent temporal and spatial occurrence of the last aperture peak in the PG, SG and LG–conditions. Only when the grip was started with a fully stretched hand the MGA was reached earlier and farther away from the target. This finding is because in some trials participants close their grip continuously after a short closing and re–opening in the beginning of the movement. However, aperture closure distance as well as the relative timing of the MGA were affected by the size of the target object. In summary, these findings neither support a fixed temporal linkage between transport and grasp components nor do they support a mere spatial coordination. In fact, our results suggest that the motor system programs and executes an effective movement which takes both, the initial aperture size and the size of the target object into account.

So far, our study replicates and extends the findings of what happens to the grip pattern when the size of the aperture is varied prior to movement onset. In the second experiment we were interested in how the grasping movement is altered if the orientation of the aperture/hand is changed prior to movement onset. This is especially interesting since it was proposed that the orientation of the hand plays a special role affecting transport as well as grasp component of the movement. Thus, we would hypothesize that altering the starting orientation of the aperture also affects the transport component of the grasping movement.

**Experiment 2**

In this experiment we investigated the effect of different start aperture orientations on grasping. Again we were interested in how the start posture of the hand is taken into account during movement execution. In contrast to Experiment 1, we hypothesized that the orientation of the grip affects both, the grip and the transport component of the movement.
Methods

Participants
Ten undergraduate and graduate students of the Ludwig–Maximilans–University Munich (four men, six women; mean age = 25, SD = 5) participated in the experiment. They were paid 8 Euro per hour for participation. All participants were right–handed by self report, had normal or corrected-to-normal visual acuity and were naive with respect to the purpose of the study.

Apparatus and stimuli
The apparatus and the general procedure were identical to Experiment 1. In this study, only one cylinder with a diameter of 40 mm was used as target object (same object as the medium–sized cylinder in Experiment 1). The cylinder could be presented at three different positions on the working surface: (a) middle: straight on from the starting position, (b) left: 45 to the left away from the starting position, (c) right: 45 to the right from the starting position (cf. Figure 7A). In all three conditions, the distance between the starting position and the object was 30 cm. Participants began each trial with their fingers closed around a wooden starting–cube (2x2x2 cm) which was placed in the middle of the working surface 12 cm away from the edge of the table. Depending on the condition, the starting–cube was oriented vertically (parallel to the sagittal plane), or the starting–cube was rotated by 45. Participants were asked to place their fingers in four different orientations on the starting–cube (Figure 7B). The different starting conditions were presented in blocks of 30 trials (10 trials per object position) with three practice trials preceding each condition. The order of blocks was counterbalanced across participants and the presentation sequence within each condition was in pseudo random order.

Participants were asked to grasp the cylinder with a precision grip using index finger and thumb to which the Polhemus sensors were attached. A third sensor was attached to the back of the hand.

Data Processing
Since the task primarily involved horizontal movements and only the horizontal orientation of the starting grip aperture was manipulated, we only analyzed the horizontal orientation of the grip (azimuth). Grip orientation is defined as the angle of the horizontal projection of the line connecting the grasping positions of the index finger and the thumb (a sagittal line corresponds to a 0 orientation of the grip and a clockwise rotation is defined as positive). This angle was determined at different moments before and during the grasping movement. The MGA was defined as the maximum distance between the index and the thumb in 3D during MT. All other dependent variables RT, MT and the parameters of the transport component were determined identical to Experiment 1.
Results

Kinematics of the grip component

Grip rotation: Our main interest lay in the alteration of the grip orientation over time. For that reason, we calculated the rotation of the grip every 5% of the movement time, as done for the aperture profiles in Experiment 1. The changes of the grip rotation over time and for the different object positions are shown in Figure 8. Visual inspection of this figure shows that the grip is mainly rotated in the first part of the movement. The final grip orientation appears to be reached at roughly 70% of MT (which corresponds approximately to the occurrence of MGA). Furthermore, we performed a repeated-measures ANOVA at 3 different moments in time (grip rotation at: (1) movement onset, (2) moment of MGA, and (3) touch of the object). At the movement onset the grip rotation was, as expected, strongly influenced by the start orientation, $F(3,27)=693.6, p<0.001$, but not by the position of the object, $F(2,18)=3.1, p=.11$. On average, the start orientation of the grip was for the -45 condition, for the sagittal start orientation, for the 45 start orientation and for the lateral start orientation.

Orientation of the grip at its maximum did depend on the start orientation, $F(3,27)=19.4, p<.001$ as well as on the position of the object, $F(2,18)=112.4, p<.001$. These effects persisted for the moment the target object was touched, $F(3,27)=14.1, p=.001$, for the start orientation and $F(2,18)=127.7, p<.001$, for the object position. None of the interactions became significant (all $p>.17$). Thus, the grip orientation at the end of the movement was still biased to the orientation of the fingers taken before movement onset (see Figure 8). The result that the orientation of the fingers is influenced by the position of the object is in line with the findings of other studies (e.g., Gentilucci et al., 1996, Roby-Brami et al., 2000, Bennis & Roby-Brami, 2002).

MGA: In order to investigate whether there is an effect of aperture orientation and object position on MGA while grasping the cylinder, a 4 (aperture start orientation) x 3 (object position) repeated-measures ANOVA was carried out. The ANOVA only revealed a main effect of start orientation, $F(3,27)=5.9, p=.006$. Participants opened their hand wider when they started their movement with the left and the sagittal start orientation compared to the right and the lateral start orientation of the aperture. No main effect of object position ($p=.26$) and no interaction ($p=.21$) was found.

Kinematics of the transport component

RT and MT: To analyze the effects of start aperture orientation and object position on RT and MT a 4 (aperture start orientation) x 3 (object position) repeated-measures ANOVA was applied on the data. No effects of the experimental variations were found on RT (all $p>.10$). However, MT was significantly affected by both, orientation of the start aperture, $F(3,27)=10.4, p=.002$ and object position, $F(2,18)=51.3, p<.001$. There was no interaction ($p=.06$). Post–hoc tests revealed that MT increases the more the start orientation was rotated clockwise being fastest in the -45 condition and slowest in the condition in which the grip was oriented laterally. Furthermore, MT was shortest when
the object was located at the right side of the working surface (613 ms ± 9 ms), slightly longer when it was presented in the middle position (668 ms ± 8 ms), and longest when it was presented at the left location (725 ms ± 8 ms).

**Velocity and deceleration:** As in Experiment 1, we characterized the transport component by the amplitude and timing of peak velocity and peak deceleration. In Figure 9a-d the mean values of all these parameters are shown. A 4 (start aperture size) x 3 (object size) repeated measures ANOVA applied on the data revealed that object position had strong effects on all wrist parameters measured (see Table 1). Further, the transport component was also very susceptible to the changes of start aperture orientation. Thus, the object position as well as the start orientation of the grip taken before movement onset influenced the kinematic parameters of the transport component.

**Coupling**

The coupling of grasp and transport component was again measured spatially and temporally. The mean opening and closing distances for the different conditions are shown in Figure 9f. A 4 (start orientation) x 3 (object position) repeated–measures ANOVA revealed no effect of the start orientation, $F(3,27)=0.3, p=.68$. However, the aperture closing distance was affected by the object position, $F(2,18)=5.3, p=.04$. The hand started to close farther away from the object when it was presented at the left position (6.9 cm ± 1.7 cm), a bit closer to the object when it was presented in the middle position (6.0 cm ± 1.4 cm), and closest to the object when it was presented to the right (5.0 cm ± 1.0 cm). We also observed a significant interaction, $F(6,54)=3.6, p=.02$, which suggests that changes in the start orientation affect the spatial occurrence of MGA differently depending on the object’s position. With respect to the relative occurrence of MGA, during MT no effect of start orientation ($p=.23$) and object position ($p=.75$) was found. On average the MGA was reached at about 70% ± 4% of MT (see Figure 9e). As in Experiment 1, we examined the temporal coupling of the transport and the grasp components further by correlating the relative time to MGA with the relative time to TPD of the transport component. When the grip was oriented to the right or the left prior to movement onset, none of these correlations were found to be significant (all $p>.07$). In the lateral condition the correlation became only significant when the right object was grasped ($r=79$ and $p=.007$, all other $p>.20$) and in the sagittal condition when the object was either presented in the middle or to the right ($r=.72$ and $p=.02$ and $r=.83$ and $p=.003$). To conclude, we observed a significant correlation only in three out of the twelve conditions presented.

**Discussion**

In this experiment we investigated the effects of changing the hand orientation prior to movement onset in grasping. We replicated the finding that the orientation of the grip axis was strongly affected by the position of the object and movement direction of the hand respectively (Gentilucci et al., 1996, Paulignan et al., 1997, Roby-Brami et al., 2000). More interesting was, however, that the grip orientation, even at the end of the movement, depended on the start orientation of the aperture. Since the target object was a cylinder, it had no specific opposition axis which had to be chosen in order to achieve a
stable grasp. The occurrence of a bias in the direction to the initial orientation suggests that the motor system takes the information about the initial posture into account while planning and executing the movement. Therefore, the experiment provides evidence that the initial hand orientation influences the selection of the grasp axis when grasping an object with a neutral orientation.

Additionally, we found an effect of the start orientation on MGA which is regarded as the main kinematic landmark of the grasp component. It should, however, be noted that the variations of the grip orientation on which we placed our emphasis always implied a rotation of the wrist. In case of the left and the sagittal grip orientation a flexion of the wrist is required whereas the right and the lateral grip orientation are linked to an extension of the wrist at the start position. Thus, we cannot clearly separate which effects are due to the orientation of the aperture and which are due to the different postures of the wrist prior to movement onset.

Furthermore, when holding the starting–cube in the different starting conditions not only the flexion and extension of the wrist changes, but also its position relative to the target object. Holding the starting–cube in the -45orientation between index and thumb requires a location of the wrist above the fingers in the direction of the working surface (see also Figure 7B). A clockwise rotation of the aperture also demands a clockwise rotation of the wrist rotating away from the working surface in direction to the participant’s body. This means the more the grip is rotated clockwise the longer the distance which the wrist has to cover to reach the target object becomes. (Note that this was also the reason why we decided to measure the transport component as the midpoint between index and thumb.) Thus, the finding that MT increases the more the start orientation of the hand is rotated clockwise might be due to the fact that movement distance of the wrist increases. The main effect of object position on MT suggesting that movements in the ipsilateral space are accomplished faster than movements in the contralateral space. Moreover, transport kinematics calculated from the midpoint of the fingers were also influenced by start orientation and object position. Thus, in contrast to the changes of initial orientation prior to movement onset (Experiment 1), the changes of initial hand orientation had considerable effects on the transport kinematics of the grasping movement.

In summary, our results show how interrelated the different components of grasping are. Varying the start orientation of the hand affected most of the parameters that characterize grasping. As discussed above, the alteration and the adjustment of the grip orientation also implies changes in the orientation of the wrist. Thus, we would argue that the orientation of the hand does not seem to constitute a third independent visuomotor channel besides transport and grasp as proposed by some theories (e.g., Arbib, 1981, Laquanti & Soechting, 1982, Stelmach et al., 1994, Fan, He, & Helms Tillery, 2006). Instead, our results support the assumption that the orientations of hand and wrist integrate the distal transport component and the proximal grasp component (e.g., Desmurget et al., 1996, Gentilucci et al., 1996).

So far we have shown that a change of aperture size (Experiment 1) and a change of aperture orientation (Experiment 2) prior to movement onset alters the execution of the grasping movement. A fundamental difference between Experiments 1 and 2 is that in case of a change in aperture size, the grasp was forced to completely adjust to the size of the target object in order to grasp it successfully. In contrast, in Experiment 2, the grip orientation did not have to be adjusted to a specific object orientation resulting in different grasp orientation in the end of the movement. In a third experiment we explored
the effects of different start orientations when a precise adjustment of the grasp axis is required.

Experiment 3

In Experiment 2 we observed that the start orientation taken before movement onset still influenced the grip orientation at the moment the target object was touched. Since the target object was a cylinder, the chosen grip orientation did not have to be very exact. In Experiment 3 we investigated the adaptation of grip orientation to a target object which required a very precise alignment of the grip axis.

Methods

Participants

Eight undergraduate and graduate students of the Ludwig–Maximilians–University Munich (three men, five women; mean age = 26, SD = 5) participated in the experiment. They were paid 8 Euro per hour for participation. All participants were right–handed by self report, had normal or corrected-to-normal visual acuity and were naive with respect to the purpose of the study.

Apparatus and stimuli

The apparatus and the general procedure were identical to Experiment 1 and 2. In this experiment, the target object was a cylinder with a diameter of 10 mm and a height of 40 mm. In contrast to Experiment 1 and 2 the cylinder was presented in a lying position meaning that it had to be grasped along the 40 mm axis (same diameter as the object in Experiment 2). Thus, the narrow ends of the cylinder represented the contact surfaces of the fingers (see inset of Figure 7A). The cylinder was presented in three different orientations: (a) sagittal: 90, (b) left: -45 to the left, (c) right: 45 to the right. The object was always presented at the same location as the central target in Experiment 2 (Figure 7A). Participants started with the same starting orientations as in Experiment 2 (Figure 7B). The different starting conditions were presented in blocks of 30 trials (10 trials per object orientation) with three practice trials preceding each condition. The order of blocks was counterbalanced across participants and the presentation sequence within each condition was in pseudo random order.

Participants were asked to grasp the cylinder with precision grip using index finger and thumb to which the Polhemus sensors were attached. A third sensor was attached to the back of the hand. All data analysis were identical to Experiment 1 and 2.

Results

Kinematics of the grip component

Grip rotation: All analyses of the aperture were performed equivalent to Experiment 2. Figure 10 shows the mean aperture orientation profiles for all start orientations and object orientations. In contrast to Experiment 2, the grip orientation was the same in the end of the movement no matter what the start orientation of the grip was. This was also
confirmed statistically. We calculated a repeated–measures ANOVA at three different moments at time. At movement onset the grip orientation was affected by the start orientation of the grip, $F(3,21)=387.4, p<.001$, but also by object orientation, $F(2,14)=9.1, p=.009$. The fact that object orientation affected grip orientation even at movement onset might most likely be due to the determination of movement onset which was defined by wrist velocity. The difference between the three orientations was, however, only about 1. At MGA the grip orientation became much stronger affected by the object orientation, $F(2,14)=100.9, p<.001$, and was still affected by the start orientation of the aperture, $F(3,21)=6.7, p=.01$. At the touch of the object, the grip orientation was no longer influenced by the start orientation, $F(3,21)=0.8, p=.46$, but, as expected it was influenced by the orientation of the object to grasp, $F(2,14)=1291.1, p<.001$. For the left oriented object the final grip orientation was , for the vertical cylinder it was , and for the right oriented cylinder grip the orientation was about . None of the interactions became significant (all $p=.31$).

**MGA:** In contrast to Experiment 2, the repeated–measures ANOVA on MGA revealed no effect of start orientation ($p=.86$). However, object orientation influenced the size of MGA significantly, $F(2,14)=15.2, p=.003$. Post–hoc tests showed that the size of MGA was smallest for the left oriented object (8.8 cm±0.2 cm), larger for the vertical object (9.6 cm±0.4 cm), and largest for the right oriented object (10.1 cm±0.5 cm). There was no interaction observed ($p=.37$).

**Kinematics of the transport component**

**RT and MT:** As in Experiment 1 and 2, RT was not affected by any of the experimental variations (all $p>.32$). Regarding the MT we found an effect of start orientation, $F(3,21)=22.2, p<.001$, replicating the finding of Experiment 2. Again, MT increased the more the start aperture was rotated in the clockwise direction being shortest for the left orientation and longest for the lateral orientation. There was also a significant effect of object orientation on MT, $F(2,14)=70.8, p<.001$. MT was longest when the object was oriented to the left (745 ms±3 ms), shorter when the object was oriented vertically (682 ms±2 ms), and shortest when the object was oriented rightward (654 ms±8 ms). There was no interaction ($p=.21$).

**Velocity and deceleration:** The transport component was again characterized by the amplitude and timing of peak wrist velocity and peak wrist deceleration (see Figure 11a–d). Similarly to Experiment 2, the start aperture orientation affected the transport component considerably (Table 1). The orientation of the object influenced the timing of peak velocity and peak deceleration but not the amplitudes. The effects of start aperture orientation and object orientation did not interact. In sum, these findings replicate the results of Experiment 2 suggesting that the start orientation of the hand influences the transport component of the grasping movement.

**Coupling**

As in Experiment 1 and 2, the coupling of grasp and transport component was analyzed
spatially and temporally. The mean opening and closing distances for the different conditions are shown in Figure 11f. A 4 (start orientation) x 3 (object orientation) repeated-measures ANOVA applied on the data showed, as in Experiment 2, no main effect of start orientation on aperture-closing distance (p=.37). However, aperture-closing distance was significantly affected by the object’s orientation, F(2,14)=9.2, p=.02. Post-hoc tests revealed that the maximal aperture opening was reached farther away from the target object if it was oriented leftward. There was also a significant interaction found here, F(6,42)=3.9, p=.02. Therefore again, the aperture closing distance did not reveal itself to be an invariant parameter in grasping.

Regarding the relative occurrence of MGA during MT, no effect of start orientation (p=.47) was observed (Figure 11e). This finding is consistent with our results of Experiment 2. The orientation of the object, however, influenced the relative timing of MGA significantly, F(2,14)=11.4, p=.003. On average the MGA occurred at 61%±5% of MT for the left oriented object, at 74%±4% of MT for the vertically oriented object, and at 74%±5% of MT for the right oriented object. There was also a significant interaction between the start orientation and the object orientation, F(6,42)=3.6, p=.03. Thus, the relative timing of MGA as well as its spatial position differed when the orientation of the object was changed, and the magnitude of this effect depended on the start orientation of the hand. As in Experiment 1 we examined the temporal coupling of transport and grasp further by correlating the relative time to MGA with the relative time to TPD of the transport component. None of these correlation were found to be significant (all p>.28).

**Discussion**

In this experiment we investigated the effect of different start orientations of the hand on grasping kinematics when the finger opposition axis must be aligned very accurately to the object opposition axis. The adjustments of the grip orientation to the object’s orientation started at movement onset and were accomplished after approximately 60% to 70% of the movement duration.

Furthermore, the grasp as well as the transport component were significantly affected by the orientation of the object to grasp. The finding that object orientation not only influences the rotation of the hand but also its opening and transport, is in line with the results of Mamassian (1997). We already discussed that the orientation of the hand prior to movement onset influences the position of the hand which could explain the effects of start orientation on MT. The same argument holds for the orientation of the object. In addition, the wrist has to be flexed when the right oriented object had to be grasped and extended when the left oriented object had to be grasped. Depending on the start orientation of the hand, this flexion and extension had to be integrated into the movement plan. Since we found no significant interaction of start orientation and object orientation on MT, the rotation of the wrist is achieved without any additional time costs, which is in accordance with the findings of Stelmach et al. (1994). However, the velocity characteristics of the transport component which were determined independent of the movement distance were also influenced by start aperture orientation as well as object orientation showing that transport parameters are susceptible to these variations.

Moreover, we observed neither a fixed temporal nor a fixed spatial coupling between grasping and transport component for the given task. This suggests that the repeatedly observed temporal coupling might be due to the non-complexity of the grasping task
used (object that was placed in front of the participants who began their movement with the fingers pinched together). Here we found that when the task becomes more difficult, involving a rotation of the fingers and the hand, the coupling between transport and grasp is altered. The finding that the aperture closing distance varies with object orientation contradicts the results of Rand and Stelmach (2005). They showed that aperture closure is generally initiated at roughly the same distance for different target orientations. Based on their data they concluded that grasping is coordinated based on spatial rather than on temporal information. However, another study by the same group proposed that aperture closing distance varied with movement speed thereby questioning the assumption that this parameter remains constant when the task requirements change.

In summary, the various effects of the start orientation and the object orientation on transport and grasp kinematics, suggest that the orientation of the hand is very closely related to both components and does not constitute a third independent visuomotor channel. If the hand orientation comes into play during grasping, the changes in movement kinematics and the interrelations appear to become much more complex. Paulignan et al. (1997) have also stated in a study that the use of a broader range of conditions changes the view on visuomotor transformations. In other words using more complex conditions reveals the interdependence of the underlying mechanisms for matching object position, orientation and size in grasping. This notion is further supported by our results.

**General Discussion**

In this study, we investigated the way in which different hand postures taken prior to the movement onset alter the kinematics of the grasping movement. We hypothesized that the assumption that grasping is a relatively stereotyped movement pattern, might be due to the fact that the movements were primarily investigated using a standard grasping task. The classical experimental grasping task requires that participants begin their grasping movement with all fingers pinched together at a given starting location which is often aligned to the body midline or slightly to the right of the participants’ body (if right handers are examined).

From these studies it is well known that: (a) the size of the object strongly influences the grasp component such as the MGA and its timing (e.g., Jeannerod, 1984, Marteniuk et al., 1990, Bootsma, Marteniuk, MacKenzie, & Zaal, 1994, Smeets & Brenner, 1999), (b) the position and the distance of the target object primarily affect the transport component of the movement such as MT and PV (e.g., Jeannerod, 1984, Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987, Jakobson & Goodale, 1991), and (c) that the orientation of the object changes the kinematics of both components, transport and grasp (e.g., Stelmach et al., 1994, Desmurget et al., 1996, Gentilucci et al., 1996, Mamassian, 1997), hence hand orientation was sometimes considered to constitute a third (independent) component of the grasping movement (e.g., Arbib, 1981, Fan et al., 2006). However, it is still a matter of debate whether the components of transport and grasp are independent of each other. Whereas studies using simple grasping tasks are in favor of two (or three) independent visuomotor channels which are merely temporally coupled (Jeannerod, 1984, Arbib, 1981), studies using more complex grasping tasks give evidence for the interdependence of all components (Paulignan et al., 1997, Desmurget et al., 1996). In addition, there are studies which are in favor of a spatial coupling of transport and grasp component (e.g., Haggard & Wing, 1998, Alberts et al., 2002, Rand &
In Experiment 1 in which only the size of the start aperture was changed prior to movement onset we replicated the finding of a substantial alteration of the grasp component while the transport component remains relatively unaffected (Saling et al., 1996; Timmann et al., 1996a). Our experiment extends earlier studies insofar as we included more conditions varying the size of the aperture at movement onset. Therefore, we could show that the closing and reopening of the aperture occurs not only when the fingers are fully stretched but also if fingers were slightly open and had to open further to grasp the object successfully. Although the distinct peak at movement onset may result in part from the release of the starting disc, the tendency to close the fingers first before starting the final grip is also preserved when there is no object to be grasped prior to movement onset.

In Experiment 2 and 3 in which we varied the start orientation of the aperture prior to movement onset, we found considerable changes in both components, manipulation and transport. While the altered start aperture in Experiment 1 selectively influenced the grasp component leaving the overall position of the hand unaffected, the variation of the start orientation was not only associated with a change of the finger position in space, but also with a change of the hand position and the rotation of the wrist. Since the selection of the finger opposition axis determines the position of the hand in work space, it seems very unlikely that the hand orientation constitutes a third independent movement component besides reach and grasp. To accomplish the task successfully all joints involved in the process of adjusting the hand orientation to the object orientation must share information during movement planning, execution and control. Thus, if the movement becomes increasingly complex the sub-processes of grasping must be integrated so that the movement is controlled holistically. It was suggested by Desmurget et al. (1996) that some "higher-order control system" might take over the integration of hand transport and hand orientation in such an event.

Regarding the coupling of transport and grasp, our results neither support a fixed temporal nor a fixed spatial relationship of both components. It has repeatedly been shown that the relative timing of MGA varies not only with object size (e.g., Marteniuk et al., 1990) but is also related to movement difficulty, such as accuracy and object visibility (for review, Smeets & Brenner, 1999). Here we could show that the timing of MGA within MT also depends on the start posture of the hand and the related task demands (as indicated by significant interactions in Experiment 1 and 3). Besides, it was proposed that the temporal linkage between grasp and transport consists in a high correlation between relative time to MGA and the relative timing of peak deceleration of the wrist (Jeannerod, 1984). However, in our data we found very few correlations between these two variables (only in some of the conditions of Experiment 2) which suggests that this relationship may change with task demands. Similarly, the distance at which the hand began to close relative to the target object varied with the task demands being in contrast with the models which predict a fixed spatial relationship (Alberts et al., 2002, Rand & Stelmach, 2005). Thus, none of the models in grasping based on an invariant temporal or spatial coupling of both components can account for our results. In contrast to these models, Marteniuk et al. (1990) suggested that transport and grasp might be primarily functionally linked, i.e. that their exact temporal and/or spatial relationship depends on the task requirements. According to this proposition the transport and the grasp components are coordinated such that a given task can be achieved efficiently and successfully. This proposition best suits our observations.
In conclusion, our experiments show that grasping kinematics change considerably if the start posture of the hand is varied. The more complex the alteration of the start posture, the more the kinematic parameters involved were affected by it. If it is necessary to adopt a certain end-posture to grasp an object successfully, the grip is mainly modulated during the first half of the movement. If there was, however, no need to adjust the hand to specific object properties (Experiment 2) then the final posture of the hand at lift-off of the object was still affected by the start posture adopted. This finding suggests that the motor system plans an economical and efficient movement taking the actual start posture of the hand into account.

References


**Acknowledgement**

This study was supported by of the Cluster of Excellence "Cognition for Technical Systems" (Project 301) and by 7th Framework Programme of the European Community (project "GRASP", ICT-215821). We thank Devika Narain for help with the data collection. We also thank two anonymous reviewers for their thoughtful comments regarding this manuscript.
Figure Legends

1. Experiment 1: The effect of the start aperture size and the object size on MGA (in cm). The mean sizes of the start aperture at movement onset in the different start aperture conditions are indicated by the black filled circles. All error bars depict ±1 SEM (between subjects).

2. Experiment 1: Mean percentage of local minima indicating a dip in the aperture profile in the different start conditions. All error bars depict ±1 SEM (between subjects).

3. Experiment 1: Representative single subject data showing a typical aperture profile (one trial) in the different experimental conditions: a) PG– condition and object size of 40 mm, b) SG– condition and object size of 55 mm, c) LG– condition and object size of 55 mm, d) FG– condition and object size of 40 mm.

4. Experiment 1: Mean time-normalized aperture profiles for the different start conditions.

5. Experiment 1: Averaged XY spatial paths over all participants for index, thumb and wrist in the different start conditions (the movement was executed from the left to the right side). The horizontal and the vertical lines show the standard deviation in x and y direction, respectively.

6. Experiment 1: The effect of start aperture size and object size on: a-d) the transport component of the movement (TPV, APV, TPD and APD); e) the averaged normalized time until the occurrence of the MGA; f) the mean distance traveled by the thumb from movement onset to MGA, and from MGA to the touch of the object. All error bars depict ±1 SEM (between subjects).

7. A: Schematic drawing of the setup of Experiment 2 (top view). The inset on the right shows the stimulus configuration used in Experiment 3. The stimuli were presented at the mid position. B: The four different start orientations of the aperture used in Experiments 2 and 3.

8. Experiment 2: Mean time-normalized grip rotation profiles for the different start orientations and object positions.

9. Experiment 2: The effect of start aperture size and object position on: a-d) the transport component of the movement (TPV, APV, TPD and APD); e) the averaged normalized time until the occurrence of the MGA; f) the mean distance traveled by the thumb from movement onset to MGA, and from MGA to the touch of the object. All error bars depict ±1 SEM (between subjects).

10. Experiment 3: Mean time-normalized grip rotation profiles for the different start orientations and object orientations.

11. Experiment 3: The effect of start aperture size and object orientation on: a-d) the transport component of the movement (TPV, APV, TPD and APD); e) the averaged normalized time until the occurrence of the MGA; f) the mean distance traveled by the thumb from movement onset to MGA, and from MGA to the touch of the object. All error bars depict ±1 SEM (between subjects).
Figure 1
Figure 2
Figure 4

- **object size 25 mm**
  - Normalized aperture in cm
  - Normalized time (100% touch of object)
  - Different line styles represent different aperture conditions:
    - Pinched together
    - Small aperture
    - Large aperture
    - Fully stretched

- **object size 40 mm**
  - Normalized aperture in cm
  - Normalized time (100% touch of object)
  - Different line styles represent different aperture conditions:
    - Pinched together
    - Small aperture
    - Large aperture
    - Fully stretched

- **object size 55 mm**
  - Normalized aperture in cm
  - Normalized time (100% touch of object)
  - Different line styles represent different aperture conditions:
    - Pinched together
    - Small aperture
    - Large aperture
    - Fully stretched
Figure 5
Figure 8
Figure 10
Table 1

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>main effect of start aperture size</th>
<th>main effect of object size</th>
<th>interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV</td>
<td>$F(3, 27) = 3.2, p = .06$</td>
<td>$F(2, 18) = 0.6, p = .51$</td>
<td>$F(6, 54) = 0.9, p = .43$</td>
</tr>
<tr>
<td>TPV relative</td>
<td>$F(3, 27) = 2.0, p = .15$</td>
<td>$F(2, 18) = 1.0, p = .37$</td>
<td>$F(6, 54) = 0.9, p = .49$</td>
</tr>
<tr>
<td>APD</td>
<td>$F(3, 27) = 1.3, p = .29$</td>
<td>$F(2, 18) = 0.7, p = .45$</td>
<td>$F(6, 54) = 0.8, p = .42$</td>
</tr>
<tr>
<td>TPD relative</td>
<td>$F(3, 27) = 0.4, p = .75$</td>
<td>$F(2, 18) = 2.2, p = .14$</td>
<td>$F(6, 54) = 2.6, p = .07$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment 2</th>
<th>main effect of start aperture orientation</th>
<th>main effect of object position</th>
<th>interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV</td>
<td>$F(3, 27) = 5.8, p = .02^*$</td>
<td>$F(2, 18) = 72.0, p &lt; .001^<em>^</em>$</td>
<td>$F(6, 54) = 8.4, p = .001^<em>^</em>$</td>
</tr>
<tr>
<td>TPV relative</td>
<td>$F(3, 27) = 11.4, p = .001^<em>^</em>$</td>
<td>$F(2, 18) = 9.6, p = .002^<em>^</em>$</td>
<td>$F(6, 54) = 6.7, p = .001^<em>^</em>$</td>
</tr>
<tr>
<td>APD</td>
<td>$F(3, 27) = 6.1, p = .01^<em>^</em>$</td>
<td>$F(2, 18) = 70.2, p &lt; .001^<em>^</em>$</td>
<td>$F(6, 54) = 4.9, p = .01^<em>^</em>$</td>
</tr>
<tr>
<td>TPD relative</td>
<td>$F(3, 27) = 4.2, p = .03^*$</td>
<td>$F(2, 18) = 36.5, p &lt; .001^<em>^</em>$</td>
<td>$F(6, 54) = 2.8, p = .06$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment 3</th>
<th>main effect of start aperture orientation</th>
<th>main effect of object orientation</th>
<th>interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV</td>
<td>$F(3, 21) = 6.4, p = .01^<em>^</em>$</td>
<td>$F(2, 14) = 0.2, p = .73$</td>
<td>$F(6, 42) = 1.3, p = .31$</td>
</tr>
<tr>
<td>TPV relative</td>
<td>$F(3, 21) = 18.6, p = .001^<em>^</em>$</td>
<td>$F(2, 14) = 73.2, p &lt; .001^<em>^</em>$</td>
<td>$F(6, 42) = 2.7, p = .09$</td>
</tr>
<tr>
<td>APD</td>
<td>$F(3, 21) = 2.3, p = .14$</td>
<td>$F(2, 14) = 1.6, p = .25$</td>
<td>$F(6, 42) = 0.1, p = .98$</td>
</tr>
<tr>
<td>TPD relative</td>
<td>$F(3, 21) = 11.3, p = .004^<em>^</em>$</td>
<td>$F(2, 14) = 34.4, p &lt; .001^<em>^</em>$</td>
<td>$F(6, 42) = 1.9, p = .16$</td>
</tr>
</tbody>
</table>

APV: amplitude of peak velocity (cm/s); TPV: relative time to peak velocity (% MT)
APD: amplitude of peak deceleration (cm/s^2); TPD: relative time to peak deceleration % MT).

Results of the repeated–measures ANOVAs applied to different dependent variables characterizing the transport component.