The Role of Object Contact

in

Pointing and Grasping

De rol van het contactmoment bij wijzen en grijpen

Proefschrift

ter verkrijging van de graad van doctor
aan de Erasmus Universiteit Rotterdam
op gezag van de rector magnificus

Prof.dr. S.W.J. Lamberts

en volgens besluit van het College voor Promoties
De openbare verdediging zal plaatsvinden op
vrijdag 20 mei 2005 om 11.00 uur
door

Marianne Biegstraaten-Meeuws

geboren te Voorburg

Promotiecommissie

Promotor: Prof.dr. J.G.G. Borst

Overige leden: Dr. G.J. Kleinsrensink
Prof.dr.ir. C.J. Snijders
Prof. U. Castiello

Copromotoren: Dr. J.B.J. Smeets
Dr. E. Brenner

In herinnering
Pa Biegstraaten ☕ 05-03-1999
Pa Meeuws ☕ 06-01-2005

Dit proefschrift werd mede mogelijk gemaakt door financïele steun van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), gebied Maatschappij- en Gedragswetenschappen (MaGW), onderzoeksnummer 425-203-03.

Contents

Chapter 1 5

General introduction

Chapter 2 15

The influence of obstacles on the speed of grasping

Chapter 3 27

Grasping the Müller-Lyer illusion: More than just a change in length

Chapter 4 43

Impact forces cannot explain the one-target advantage in rapid aimed hand movements

Chapter 5 57

The relation between force and movement when grasping an object with a precision grip

Chapter 6 80

Summary and conclusions

Hoofdstuk 6 91

Samenvatting en conclusies

References 101

Dankwoord 107

Curriculum Vitae 109

Publications 111

Chapter 1

General introduction

Think of the following: You are at the dining table eating breakfast. You experience a sudden need for chocolate; you want to have chocolate flakes on your bread. You reach out your arm just over a hot cup of tea and you manage to avoid the not so interesting peanut butter and the cheese that each are at one side of the desired chocolate flakes. You place your fingers at each side of the packet with chocolate flakes and lift it to bring to your plate and spread the flakes all around your slice of bread. The movements described in this short story about how we grasp an object to lift it and use it for some particular goal do not seem complex. Most of us can perform similar tasks without any difficulty. But in fact it is a very complex task in which our brain has to control and organise a lot of different events.

This thesis is written in an attempt to show *how* and *what* we control when we reach with our arm and grasp with our fingers. Is reaching for the packet of chocolate flakes separately planned from adjusting our fingers to grasp the packet, or not? What is the influence of the peanut butter and cheese just beside the chocolate flakes? And does it matter how we make contact with the surface of the packet of chocolate flakes?

Functional anatomy of the hand

An apparently simple every day task like grasping an object, appears much more complex when one considers how the fingers and the hand are built. About 30 different muscles control the hand. Some of these muscles originate in the forearm while others originate in the hand itself. Each finger is controlled by a different set of muscles and therefore we are able to generate different kinds of grasps by a very fine control (see figure 1.1). For picking up a knife we close our fingers around the handle, while the thumb rests at the opposite side of the knife's handle (figure 1.1A). For picking up an egg we will use another grip, for instance as in figure (1.1B).

The large number of different muscle groups and joints enable us to make many different movements. However, many degrees of freedom are difficult to control. Therefore, the skeletomotor system reduces the complexity of the task by consistently using more or less fixed coordination patterns between certain muscles (Santello et al. 2002; Santello et al. 1998; Soechting and Flanders 1997). There exists some mechanical coupling of soft tissue (tendons and ligaments) and muscles

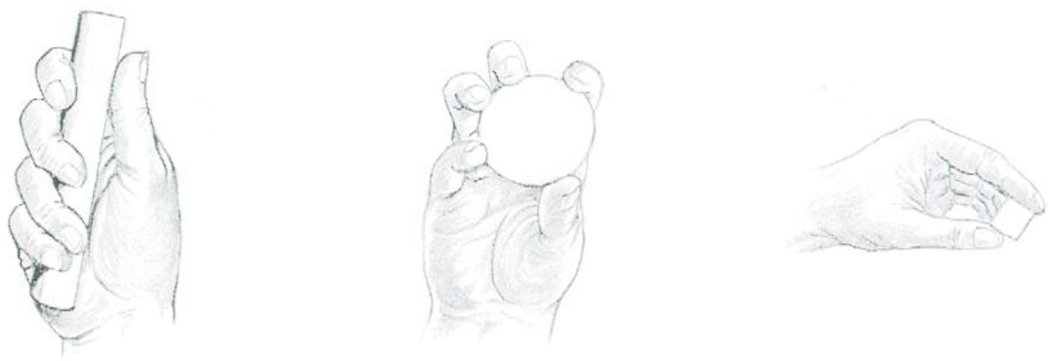

Figure 1.1 *Examples of different grasps.* **A.** *Power grasp.* **B.** *precision grip between thumb and all fingers.* **C.** *Precisiongrip between index finger and thumb. Derived from Rozendahl et al. 1990.*

(extensor digitorum communis, flexor digitorum profundus) between the separate fingers so that they can act as a whole (Keen and Fuglevand 2003; Kilbreath et al. 2002; von Schroeder and Botte 1993; von Schroeder et al. 1990). Co-contraction of several muscles can also stabilize the hand while lifting an object.

All these reductions in degrees of freedom are necessary to be able to control a complex system like the hand and finger. In contrast, we are still able to form different kinds of grasps by making particular movements for each finger separately. Controlling the movements of the hand and finger is thus simplified by reducing the number of degrees of freedom, while on the other hand there remains a considerable amount of individuality for each digit to allow fine manipulative movements.

Neural control

Many neural structures are involved to control a complex system like the hand and fingers. The primary motor cortex together with several premotor areas of the brain is crucial for normal control of hand function. Each single neuron in the primary motor cortex can innervate multiple forearm muscles as well as multiple hand muscles (Buys et al. 1986; Fetz and Cheney 1980; Shinoda et al. 1981; Shinoda et al. 1979). However, a specific muscle can be innervated by multiple neurons which are spread in a large area of the motor cortex (Landgren et al. 1962). These areas of the motor cortex for individual muscles may overlap (Andersen et al. 1975; Donoghue et al. 1992). Both the premotor areas as the primary motor cortex get input from the basal ganglia and from parts of the cerebellum. Together, the highly distributed network of neurons and their connections to the muscles makes it possible for us to perform highly coordinated tasks, while maintaining a high degree of individual finger movements.

Describing grasping movements

The variables studied in grasping behaviour are mainly the grip aperture between the fingers (mostly between index finger and thumb as in figure 1c), the movement time and the velocity of the hand. While reaching out our arm to grasp an object, our fingers start to open till a certain maximum. This peak grip aperture (PGA) is larger than the width of the object and is reached in the second half of the movement time (Jeannerod, 1981). After the PGA, the fingers close again until they have contacted the object. The PGA becomes larger when a larger object is grasped, e.g. it scales with object size (Marteniuk et al. 1990). For larger objects the PGA occurs relatively later in time.

Predicting which neurons will be active during a movement is still very difficult. Due to the complexity of the musculoskeletal system, similar movements do not have to be controlled in a similar manner. An extreme example of this is given in the study of Wing and Fraser (1983). The grasping movements of a patient with a thumb prosthesis were very similar to that of healthy subjects. However, in contrast to the control of a normal thumb, the patient controlled his prosthetic thumb with some shoulder muscles.

Modelling grasping *behaviour* therefore does not give any insight in which neural structures control the grasping movement exactly, since similar movements do not have to be controlled by the same neurons. Modelling grasping movements does give insight in the variables or parameters that are important to grasping behaviour. By manipulating these parameters in an experimental set up we can describe and interpret the resulting grasping behaviour. Since grasping involves several joints and fingers one should be careful in choosing the variables to study.

The classical view: two visuomotor channels

Jeannerod (1981; 1984) proposed a view on the control of grasping behaviour based on the separation between the rather fast reaching movement of the arm and the slower grasping movements of the fingers relative to the wrist (Arbib 1981). The fast reaching movement brings the hand near the *location* of the object in space (*transport component*). The shaping of the fingers (*grip component*) is tuned by the *size* and the *shape* of the object in such a way that the fingers can successfully close around the object.

In this classical view the object properties such as the location, size, shape and orientation all are transferred into different motor commands. The transport component and the grip component are related to separate and independent visuomotor channels. As mentioned above, each channel has its own input and output. The location of the object (extrinsic property) is the main input for the visuomotor channel reflecting the transport component. Altering the location of the object will lead to changes in movement time and to changes in the trajectory of the wrist. Since both components are thought to reflect independent visuomotor channels, altering the location of the object to be grasped will not lead to any changes in variables related to the grip component (PGA). The separation in a transport component and a grip component is widely accepted and extensively used to describe grasping movements

Anatomical support

The independent visuomotor channels for reaching and for grasping connect from the primary visual cortex (V1) to the primary motor cortex. The pathway for reaching (transport component) includes the lateral and medial intraparietal areas (LIP and MIP) and parieto- occipital area (PO) which project to the premotor cortex. In these parietal areas populations of neurons respond specifically to certain locations of an object in space (Hyvarinen 1982; Kalaska et al. 1983; MacKay 1992).

The separate pathway for grasping (grip component) involves the anterior intraparietal area (AIP) (Binkofski et al. 1998; Culham et al. 2003). In this area neurons are mostly active while the fingers move to form a specific grasp for a particular object, irrespective of the location of that object in space (Sakata et al.

1997; Sakata et al. 1999). AIP projects directly to a small part of the premotor cortex (F5).

Independent or not?

Several authors showed that the transport and grip component are not completely independent. Therefore totally independent pathways cannot explain the highly coordinated grasping movements of human. Since two visuomotor channels are used to achieve the one goal (lifting the object) it is not unreasonable to think that both channels should interact somewhere. Jeannerod (1999) claimed that there indeed could be some coordination between both components, but there could only be an influence from transport component to the grip component, not the converse.

An alternative view

Smeets and Brenner (1999) proposed an alternative view to that of Jeannerod. Smeets and Brenner do not use the well-established concept of a separately controlled transport and grip component. They based their view on the notion that a grasping movement is similar to a pointing movement, but only executed with two fingers instead of one. To grasp the packet of chocolate flakes at the breakfast table successfully, we first have to select suitable grasping points on the surface. To be able to easily lift the packet of chocolate flakes, the line connecting both grasping points on the surface should go either trough or above the centre of mass of the packet. Otherwise the packet will turn when we lift it up. How accurately we place the fingers on the surface further depends on the roughness of the surface and on the weight of the object.

Smeets and Brenner (1999) assumed that grasping is the same as pointing, but only executed with index finger and thumb. In their view, the index finger and thumb move more or less independently to their designated positions on the surface of the object. Obviously the digits can’t move totally independent because they are anatomically linked. However this is not important for how grasping behaviour is controlled. Grasping movements are shown to be similar when fingers of the same

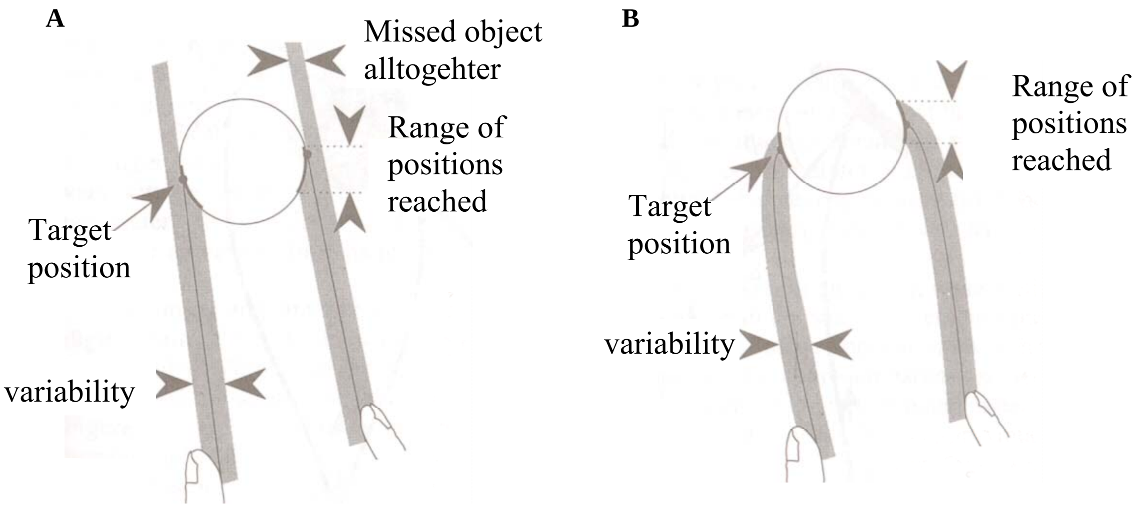

Figure 1.2 *Trajectories of index finger and thumb towards an object. If the trajectory is straight (***A***), some variability in the path will lead to large errors in the end positions at the object. In contrast, when the trajectory is curved so that the fingers approach the object perpendicularly (***B***), some variability in the path will only have minor effects on the end position at the object. Derived from Smeets and Brenner (1999).*

hand, fingers of both hands and even when fingers of two different subjects are used to grasp an object (Burstedt et al. 1997; Smeets and Brenner 2001).

If people point to a target with one finger, they generally do not move in a straight line. Near the target, the trajectory of the finger tends to curve a bit. By doing this, the chance that the finger contacts the surface at the designated contact point is very high. Small variability in an approximately curved trajectory only causes minor errors in the endpoint of the movement of the finger on the target. In contrast, the same amount of variability in a straight trajectory leads to a lower chance of contacting the target at the designated point (figure 1.2).

Modelling two pointing movements

Flash and Hogan (1985) modelled pointing movements by minimizing the derivative of the acceleration (minimum-jerk) of the hand. This model describes smooth pointing movements with a bell shaped velocity profile of the hand and with some constraints at the end and beginning of the movement.

Smeets and Brenner (1999) adjusted the model for pointing of Flash and Hogan (1985) in such a way that it could be used for grasping movements. They included their assumption that people tend to approach the surface of the object perpendicular. They modelled this perpendicular approach by taking a non-zero deceleration at the end of the movement. This final deceleration was scaled by the squared movement time. The resulting parameter has the dimension of length and describes the way the digits approach the object. The larger this approach parameter (a_p), the more perpendicular the digits approach the surface of the object.

Back to the breakfast table: Short outline of this thesis

Avoiding the peanut butter and cheese

The movement time of a reach-to-grasp movement increases when people grasp an object that is flanked by obstacles at each side, like the peanut butter and cheese at the breakfast table in the first paragraph of this introduction. The hand slows down to increase accuracy and thereby to prevent touching the obstacles. How much the movement time increases depends on the size of the gap between the target and the obstacle (Tresilian 1998). In *chapter 2* we show that the movement time is mainly determined by the gap between the object and the nearest obstacle. Whether the smallest gap is at the side of the index finger or at the side of the thumb does not seem to be important for avoiding these obstacles. This provides additional evidence for the hypothesis index finger and thumb are controlled independently during grasping.

In *chapter 3* we look at what happens when an object is placed in a pictorial illusory surrounding. Illusions are known to change the perceived length of an object. Can this perceived length of the object explain the effects seen on a grasping movement towards an object placed in an illusory surrounding? Or are these effects due to a change in perceived accuracy caused by parts of the pictorial illusion being perceived as obstacles? We used the model of Smeets and Brenner (1999) to predict the effects of both a change in perceived length and a change in perceived accuracy on grasping movements. These predictions are compared to the experimental results.

Touching and grasping the packet of chocolate flakes

An important parameter in the model of Smeets and Brenner is the impact with the surface of the object when making contact. In *chapter 4* we modelled the impact with the target for pointing movements. Contacting a target with a large force could in principle explain the differences in timing found between pointing to a single target and pointing to the first target of a sequence of targets. The model predictions are compared to the results of an experiment in which subjects have to point as fast as possible to just a single target, or to multiple targets in a row. Movements to the first target are faster when subjects do not have to move on to another target, but we found that this was not due to a larger applied force to the first target.

If this is so for pointing movements then what happens while the fingers make contact with an object when grasping it? Can we indeed describe grasping movements in terms of pointing with two independent fingers and do the fingers approach the object perpendicularly? In *chapter 5* we describe the way in which people make contact with the object with their index finger and thumb. We measured the position of the fingers in synchrony with the forces applied to the object.

Chapter 2

The influence of obstacles on the speed of grasping

Abstract

The movement time of a reach-to-grasp movement increases when obstacles are placed close to the target object. We investigated whether this increase can best be explained by limits on the grip aperture or by limits on the paths of the individual digits. In our experiment subjects were instructed to pick up an object with their index finger and thumb. There was an obstacle at either side of the object. A model in which the movement amplitude and the distance between each obstacle and the target object are independent factors best described the increase in movement time when either obstacle was placed closer to the object. We conclude that the way that obstacles influence the movement time in reach-to-grasp movements is determined by the extent to which they limit the digits' paths.

Introduction

Placing an obstacle near the target of a reaching movement influences the kinematics of the hand: the movement time increases. The reaching movement slows down to increase accuracy and thereby prevent the hand from touching the obstacle. How much the movement time increases depends on the gap between the target and the obstacle (Tresilian, 1998). When grasping an object between obstacles, there is more than one gap. What could determine movement time in this situation? The answer depends on how one thinks that grasping is controlled.

According to a hypothesis proposed by Jeannerod (1988, 1999), grasping an object consists of two more or less independent components. According to this *grip control hypothesis*, the wrist is transported towards the target object (transport component) and the fingers move relative to each other to grasp the object (grip component). Obstacles can influence each of these components. However, the wrist (thus the transport component) does not come near to the target object and obstacles. Therefore it is not clear in this view why the transport component should be influenced by the presence of obstacles *beside* the target.

Recently, Smeets & Brenner (1999) proposed an alternative for the grip control hypothesis for grasping. They argued that in grasping the tips of the finger and thumb can be regarded as moving independently towards their designated places of contact on the surface of the object. The hand or the wrist does not play a role in their model. Obviously the digits cannot move completely independently, because they are anatomically linked. However, experiments have shown that the anatomical constraint does not have much influence on grasping (Smeets & Brenner 2001). Thus assuming that the tips of the digits move independently is not totally unreasonable. According to this *digit control hypothesis*, the characteristic grip preshaping is a result of the requirements of the task: both digits should arrive simultaneously and approximately perpendicular to the surface. The requirement of arriving simultaneously, so as not to knock over the object and being able to continue to lift the object in a single smooth movement, means that a single obstacle will not only influence the movement time of the digit that it is obstructing, but will influence the movement time of both digits to a similar extent.

To discriminate between the two above-mentioned hypotheses on grasping, Mon-Williams & McIntosh (2000) performed an experiment involving obstacle avoidance. In their study, subjects were asked to reach for and pick up an object that was flanked by obstacles both at the side of the index finger and at the side of the thumb. The position of the obstacle at the side of the index finger was varied. Movement time was measured for each trial. Based on Fitts' law (Fitts 1954; Fitts & Peterson, 1964) Mon-Williams & McIntosh (2000) defined an index of difficulty (ID) both for the grip control hypothesis (named *visuomotor ID* by Mon-Williams & McIntosh, further referred to as *grip ID*) and for the digit control hypothesis (named *digit ID* by Mon-Williams & McIntosh, further referred to as *average ID*). In accordance with Fitts' law, Mon-Williams & McIntosh (2000) defined the ID as $\log_2$ (2A/W), with A being the amplitude of the movement (20 cm or 30 cm) and W the target width according to each of the hypotheses. For the *grip ID* they used the total distance between both obstacles (grip size) as the target width. For the *average ID* they calculated a separate index for each digit, using the gap between the obstacle and the target at that side as target width, and averaged the indices for index finger and thumb. Movement time was plotted as a function of these indices of difficulty. Movement time was more closely related to the *grip ID*, which they considered to support the grip control hypothesis. We have objections to their experiment and analysis.

We question whether Fitts' law is valid if the movement amplitude and the target width are perpendicular to each other, as is the case for avoiding obstacles while grasping. The index of difficulty that Fitts used to derive his law is based on the amount of information (number of bits) used in the specification of movement distance. This amount of information only predicts the accuracy in the direction of motion. Fitts' law was also verified in experiments in which the target size was varied in the same direction as the movement amplitude (Fitts 1954; Fitts & Peterson, 1964, see Plamondon & Alimi (1997) for an overview).

In order to judge whether Fitts' law was appropriate for the obstacle avoidance data in Mon-Williams & McIntosh study, we replotted the data of Mon-Williams & McIntosh (2000) in figure 2.1, adding different symbols for the different reaching distances. There appear to be systematic differences between reaching distances: open and closed symbols appear to each form a separate curve. Since Fitts' law was supposed to get rid of such differences, the use of Fitts' law may not be appropriate to describe the effect of obstacles on grasping in this configuration. However, in order to keep in line with the reasoning of Mon-Williams & McIntosh (2000), we used another way to quantify the difficulty of the task.

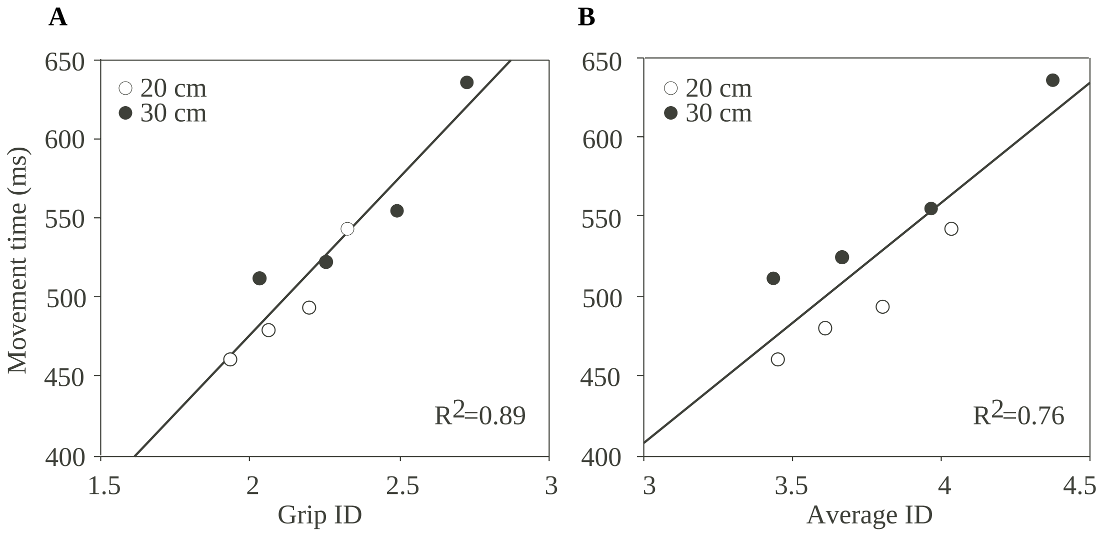

Figure 2.1 *Plots of the data of Mon-Williams & McIntosh (2000). Regression plots for movement time against the grip ID (***A***), and average ID (***B***), as defined in the methods section. Open and filled symbols represent data at a reaching distance of 20 cm and 30 cm, respectively. Note that the numbers on the horizontal axis in* ***A*** *and* ***B*** *are different from those in figures 2 and 3 of Mon-Williams & McIntosh (2000), because the numbers in the latter figures are not correct (Mon Williams, personal communication). Furthermore, the R^2 values differ because we did not remove outliers.*

Based on similar findings Welford et al. (1969) formulated a model in which movement amplitude (*A*) and target width (W_i) are independent factors. This model is described by the following equation:

$$MT = a * \log_2 \frac{A}{W_0} + b * \log_2 \frac{W_0}{W_i}$$

with *a* and *b* being independent constants for amplitude and target width respectively. W_0 is the "assumed accuracy without visual control" (Welford et al., 1969). We will call $\log_2 \frac{W_0}{W_i}$ the target difficulty and $\log_2 \frac{A}{W_0}$ the distance difficulty. How this model can be applied to grasping will be explained in the methods section.

In the experiment of Mon-Williams & McIntosh, the positions at which the subjects had to grasp the object were not controlled. According to Tresilian (1998) and Jackson et al. (1995), objects placed at the side of the thumb have less influence on the movement time of prehension than objects placed at the side of the index finger. This may appear to be inconsistent with both models, but it is easily explained by the tendency to place the thumb nearer to oneself and the finger slightly behind the object. Thus, objects placed at the two sides have different effects because the digits are positioned asymmetrically. When grasping in a natural manner, as was done in the experiment of Mon-Williams & McIntosh, the trajectory of the thumb is straighter then that of the index finger, making a collision between thumb and obstacle less likely. The asymmetrical grip can be avoided by indicating where the index finger and thumb should contact the object. If index finger and thumb move to equivalent positions on the target object (i.e. equal distance from the subject), the task constraints are expected to be the same for both, so the influence of the obstacle should also be the same. We verified this by varying the obstacle positions at both sides of the target object.

Mon-Williams & McIntosh (2000) only varied the position of the obstacle at the side of the index finger. We repeated their study, but in contrast varied the distance between the obstacle and the target object both at the side of the index finger and at the side of the thumb. To ensure that the constraints were equal for the index finger and thumb, as explained above, subjects had to grasp the object at marked positions.

Methods

Subjects

Six subjects (four men, two women) volunteered to take part in the study after being informed about what they would be required to do. They were instructed to reach for, grasp and lift an object with their index finger and thumb, and to put it at a marked position on the table. This study is part of an ongoing research program that has been approved by the local ethics committee.

Experimental set-up

We designed the set-up to be as close as possible to that of Mon-Williams & McIntosh. The main difference is that we varied the positions of *both* obstacles. Obstacles were placed at either side of the target object (see figure 2.2). The target object (6 cm height x 3 cm width x 2 cm depth) and the obstacles (20 cm height x 3 cm width x 1 cm depth) were rectangular wooden blocks. Two black marks at the middle of the lateral sides of the target object indicated where the subject was expected to make contact with the object.

The target object was placed either 20 or 30 cm from the starting point. When it was 20 cm from the starting point there was a gap of 2 cm, 2.75 cm, 3.6 cm or 4.5 cm between the target object and the obstacle at one side. The obstacle at the opposite side was placed 3 cm from the target object. When the target was 30 cm from the starting point, the gap was 2.1 cm, 3.7 cm, 5.6 cm or 7.7 cm at one side and 4 cm at the other side. For each reaching distance the variable gap between obstacle and target object could be at either side of the target object. Ten movements were recorded for each obstacle position, resulting in a total of 160 trials (2 reaching distances, 4 gaps, 2 sides, 10 repetitions).

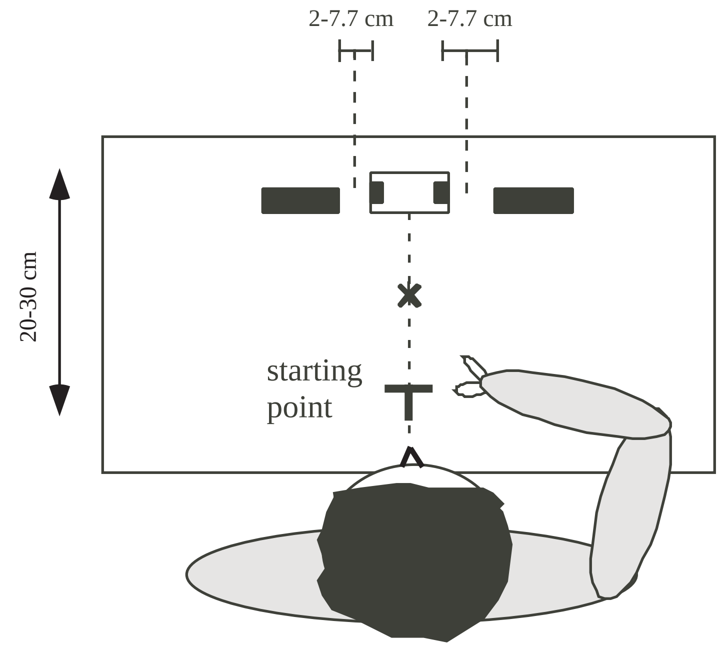

Figure 2.2 *Experimental set-up (not to scale). The target object (white rectangle) had to be grasped at the marked positions at the left and right side of the target. Obstacles (black rectangles) were placed at both sides of the target object.*

The positions of four infra-red-emitting diodes (IREDs) were measured with an Optotrak motion recording system. Two IREDs were placed on the distal phalanx of the thumb and index finger. The other two IREDs were placed on the target object. Positions of all IREDs were recorded for a period of 2 seconds at a sampling rate of 250 Hz.

Procedure

The hand was placed in the neutral position between pronation and supination with the thumb and index finger touching each other at the starting point. After the experimenter had given a verbal sign, the subjects reached for the object. They were instructed to reach as fast and accurately as possible without touching the obstacles, to pick up the object, and to place it at a marked position on the table (figure 2.2). The subjects were specifically instructed to grasp the target object at the marked positions. Trials in which the obstacles were touched were immediately re-run. The number of trials that were re-run varied between 0 and 14% across subjects.

Data analysis

Velocity was calculated by numerical differentiation of the position data. Movement onset was defined on the basis of the component of the velocity in the direction of the target. It was defined as the first frame of this velocity component after the last zero crossing before peak velocity. The offset of the movement was defined as the lift of the target object, using a similar velocity criterion. A median value of the MT was obtained for each subject in each condition. A paired t-test was carried out to determine whether the side at which the obstacle was varied influenced the MT.

We used multiple regression analysis to fit the Welford model to the data. We did this for both hypotheses, and both for our own data and for those of Mon-Williams & McIntosh (2000). For the regression analysis of our own data, we first averaged the MT values over subjects. We assume that W_0 (2.37 cm) is the same as in Welford et al. (1968). For our data, the goodness of fit of the Welford model was assessed quantitatively with a χ^2 test (Press et al., 1990). This is a way to test if the model fits the data points well, given the standard errors of the data points.

For the grip control hypothesis W_i is simply the total distance between the obstacles:

$$MT = a * \log_2 \frac{A}{W_0} + b * \log_2 \sqrt{\frac{W_0^{\,2}}{grip^2}}$$

Smeets & Brenner (1999) assume, in their view on the control of grasping, that index finger and thumb move independently towards positions on the target object. Considering the constraints of a grasping task, whereby the digits should arrive more or less simultaneously, one would expect movement time to be equally influenced by the gap at the side of the index finger and at the side of thumb. However, it is very unlikely that the *average* difficulty is critical, because shifting a near obstacle slightly closer constrains the movement to a much greater extent than does shifting a distant obstacle slightly closer. We therefore extended the equation of Welford et al. (1969) for the digit control hypothesis by replacing the target difficulty by a term that considers the distance between each obstacle and the target object:

$$MT = a * \log_2 \frac{A}{W_0} + b * \log_2 \sqrt{\frac{W_0^{\,2}}{finger\ gap^2} + \frac{W_0^{\,2}}{thumb\ gap^2}}$$

Finger gap and *thumb gap* are the distances between each obstacle and the target object.

Results

In figures 2.3A and 2.3B we replotted the data of Mon-Williams & McIntosh (2000; see figure 2.1) in terms of the equations adapted from Welford et al. (1969). The figures show the MT as a linear function of the target difficulty and an independent distance difficulty for both the grip hypothesis (R^2=0.93) and the digit hypothesis (R^2=0.99). The constants for distance difficulty and target difficulty are *a*= 266 ms and *b*=88 ms for the grip control hypothesis and *a*=157 ms and *b*=117 ms for the digit control hypothesis. These fits are much better than the original regressions in figures 2.1A and B, which justifies our choice for this analysis.

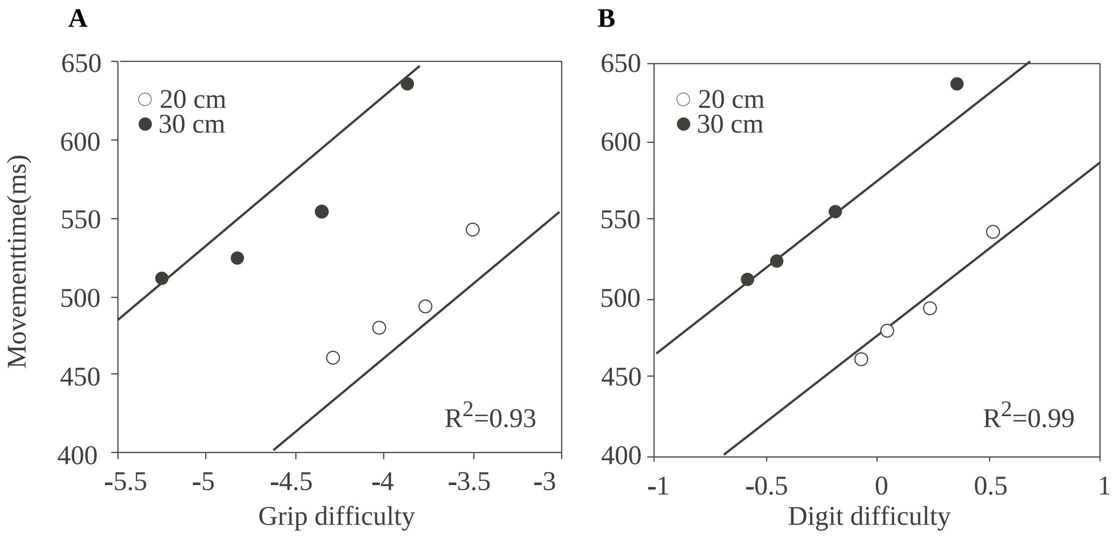

Figure 2.3 *Plots of the data of Mon-Williams & McIntosh (2000). Regression plots for movement time against* *the grip difficulty* (**A**) *and* *digit difficulty* (**B**)*, as defined in the methods section. Open and filled symbols represent data at a reaching distance of 20 cm and 30 cm, respectively.*

Figures 2.4A and 2.4B show the MT's of our own experiment plotted against the target difficulty for the grip hypothesis (R^2=0.65) and the digit hypothesis (R^2=0.79) respectively. The higher R^2 value for the regression based on the digit control hypothesis (as found in figure 2.3) implies that variations in MT are better predicted by the gap between each of the obstacles and the target object than by the total gap between the obstacles. The χ^2 test reveals a significant deviation from the regression fit based on the grip control hypothesis at both 20 and 30 cm distance (χ^2_{14}=65.2 p<0.001). For the digit control hypothesis there is no such deviation (χ^2_{14}=9.5, p=0.80) . The digit control model thus fits the data adequately (taken into account the standard errors of our data points), whereas the grip control model can be rejected. The constants for distance difficulty and target difficulty are a= 402 ms and b=179 ms for the grip control hypothesis and a=180 ms and b=305 ms for the digit control hypothesis. The sides at which the obstacle's distance was varied did not significantly influence the MT (p=0.29; circles and squares in figure 2.4).

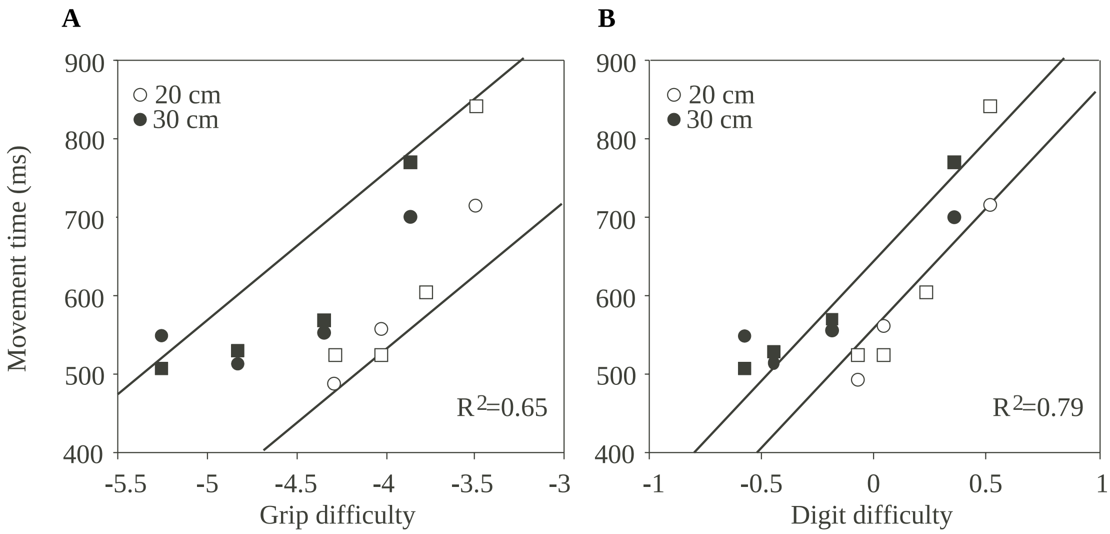

Figure 2.4 *Plots of our own data. Regression plots for movement time against* <u>*grip difficulty*</u> (**A**) *and* <u>*digit difficulty*</u> (**B**)*, as defined in the methods section. Each point represents the average movement time of six subjects for one of the sixteen conditions. Open and filled symbols represent data at a reaching distance of 20 cm and 30 cm, respectively. Circles indicate trials in which the obstacle at the side of the thumb was varied. Squares indicate trials in which the obstacle was varied at the side of the index finger.*

Discussion

An obstacle can influence the time it takes to grasp an object. Based on different hypotheses for the control of grasping, one can argue that movement time is influenced either by a limitation on the grip aperture or by a limitation on the paths of individual digits. In our replication of the experiment of Mon-Williams & McIntosh (2000), we varied the obstacle positions at both sides of the target object. We instructed the subjects to grasp the target object at specified marks in order to ensure that the same obstacle distance leads to the same constraint for both digits. In the study of Mon-Williams & McIntosh no specifications were made, so that subjects could make the task easier and move faster by not grasping all targets at the same contact positions. We think that this difference in constraints caused the much larger range of MT's in our data (figure 2.4) than in the original study of Mon-Williams & McIntosh (2000) (figure 2.3). Mon-Williams & McIntosh analysed their data in terms of Fitts' law. A consequence of Fitts' law is that the movement time plotted as a function of an ID is independent of the movement amplitude. The use of Fitts' law was not appropriate for our task, because the relationship between MT and the index of difficulty did depend on the amplitude of the movement (compare open and filled symbols in figure 2.1). Therefore we used a model in which movement amplitude and target difficulty are independent factors instead (figures 3 and 4). The main result was a better fit with *digit difficulty* than with the *grip difficulty*. The influence of obstacles is thus better explained by the *digit control hypothesis* than by the *grip control hypothesis*. The "third-way" hypothesis proposed by Mon-Williams & McIntosh (2000), also contains a grip component and is therefore also less suitable. Besides there being a more linear relationship between MT and obstacle position, there are two more aspects of the data that are in favour of the digit control hypothesis of Smeets & Brenner (1999).

Firstly, in our experiment varying the positions of the obstacles had a significant effect on the movement time. According to the grip control hypothesis, the transport component and grip component are controlled independently. Several studies (Marteniuk et al, 1990; Paulignan et al, 1991; Bootsma et al 1994) have already shown evidence for interactions between the two components. Jeannerod (1999) summarised these results with the claim that the transport component can influence the grip component, but not the converse. If so, it is not clear why obstacles placed beside the target object, which only imposes restrictions on the grip component, should influence movement time.

Secondly, in contrast to Tresilian (1998) and Jackson et al. (1995), we found that the side at which the position of the obstacle was varied made no difference to the MT (figure 2.4, squares and circles). This is presumably because we forced our subjects to grasp symmetrically. This is consistent with the digit control hypothesis in which a grasping movement is constrained by the demands on the independent digits, without consideration of any of the anatomical differences between index finger and thumb.

We conclude that a model based on the control of the individual digits can best explain the influence of obstacles on a reach-to-grasp movement.

Chapter 3

Grasping the Müller-Lyer illusion:
More than just a change in length

Abstract

The peak grip aperture is larger when grasping a large object, than when grasping a small object. Peak grip aperture has therefore often been used to study how visual size information is used for guiding movements towards objects. We question this method because the reverse, that a larger grip aperture denotes a grasp towards a larger object, is not necessarily true. The difficulty of a movement could also influence the grip aperture. This issue is particularly relevant when distinguishing between a direct influence of an illusion and non–illusory effects of the graphical elements that cause visual illusions. To illustrate this we let people grasp a bar that was superimposed on the shaft of a Müller-Lyer figure. The configuration of the Müller-Lyer figure and the starting position of the hand affected the peak grip aperture, its timing and the movement time. The configuration also affected the final grip aperture, although the influence was very small. We argue that these effects on grasping cannot be explained by the illusion's influence on the judged size alone. Thus the graphical elements must also influence the movement in other ways than by changing the perceived size.

Introduction

When reaching to grasp a real object, the fingers open to a certain maximum and then close again until they contact the object (Jeannerod 1984). The peak grip aperture (PGA) scales linearly with object size (Marteniuk et al. 1990). PGA is usually interpreted as reflecting the size estimate used by the motor system. It has therefore been used to study the influence of illusory surroundings on such visual size estimates. We question this method because although a larger object is approached with a larger PGA, the reverse is not necessarily true. A larger grip aperture can also be caused by other factors, such the size and roughness of the contact surface, viewing conditions, timing constraints (Smeets and Brenner 1999) or the presence of obstacles near the target object. We will summarize all these effects by the term “judged difficulty”.

Non-illusory effects of an illusory context could change the judged difficulty of the movement, and thereby influence the PGA when grasping the object within that context. Some authors have even proposed that non-illusory effects are responsible for all of the influence that illusions have on grasping (Haffenden et al. 2001). A possible reason for such an influence is that parts of the illusion could be treated as obstacles. This interpretation is consistent with the idea that illusions do not influence our actions (Haffenden and Goodale 1998) and with the idea that judgements of size do not guide human grasping (Brenner and Smeets 1996; Smeets and Brenner 1999). However, other authors interpret the same data in a more straightforward fashion. They argue that the illusion influences visual judgements of size, and that these judgements guide the grip aperture when grasping the objects (Franz 2001; Franz et al. 2003; Franz et al. 2001; Franz et al. 2000; Pavani et al. 1999).

Looking at influence on PGA alone is unlikely to resolve this difference, because both illusory size information and illusory difficulty could be responsible for any given change in PGA. Finding the influence that one expects on the basis of the illusion's influence on the perceived size could be a coincidence, while not doing so could mean that the task used to determine the perceived size was inadequate. Smeets, Glover & Brenner (2003) have shown that a change in the judged difficulty of the movement could explain more aspects of grasping an object placed on the central part of the Ebbinghaus illusion than only the change in PGA induced by the flankers. They did so using a model for grasping which assumes that finger and thumb move more or less independently towards their designated places of contact on the surface of the object (Smeets and Brenner 1999; 2001). In the present study we try a more direct approach to showing that the change in perceived size cannot be the only factor involved in the Müller-Lyer illusion's influence on grasping.

In order to find a more direct approach we turn to the minimum-jerk model that Smeets & Brenner (1999) used to describe grasping movements with constraints at the beginning and the end of the movement. The model parameters are movement time, the initial and final positions of the digits, a velocity and deceleration of zero at the beginning of the movement and a velocity of zero at the end of the movement. The deceleration was not zero at the end of the movement, and was scaled by the squared movement time to get an "approach parameter" (a_p) the larger this parameter, the more perpendicularly the digits approach the object's surface. With this model, a larger PGA can be obtained either by changing the digits' final positions (in accordance with a change in perceived size) or by changing the approach parameter (in accordance with a change in difficulty). Choosing a larger object leads to a larger PGA later in the movement (figure 3.1A), whereas choosing an object that is more difficult to grasp leads to a larger PGA earlier in the movement (figure 3.1B). A review of the literature (Smeets and Brenner 1999) confirmed that the relative time to PGA (TPGA) depends both on the size of the object and the difficulty of the movement. Thus TPGA could help us to distinguish between the influences of incorrect size information and of changes in judged difficulty.

If the above-mentioned model is correct, then the extent to which the judged difficulty influences the PGA and its relative timing will depend on the MT, which is also influenced by the difficulty (Fitts 1954). Therefore, if one wants to distinguish between the use of misjudged size information and illusory difficulty, it is not enough to analyse the PGA and the TPGA, but one must also consider the total movement time (MT). However, that is still not enough. The relationships mentioned above hold for real changes in size. Figure 3.1C shows simulated trajectories that illustrate how a movement aimed at a physically larger object (thick solid line) and a more accurate movement (dashed line) can cause an equal increase in PGA (for the same MT). However these are simulated movements towards real physical objects. Illusions can change the apparent size of a superimposed object, but they do not change its physical

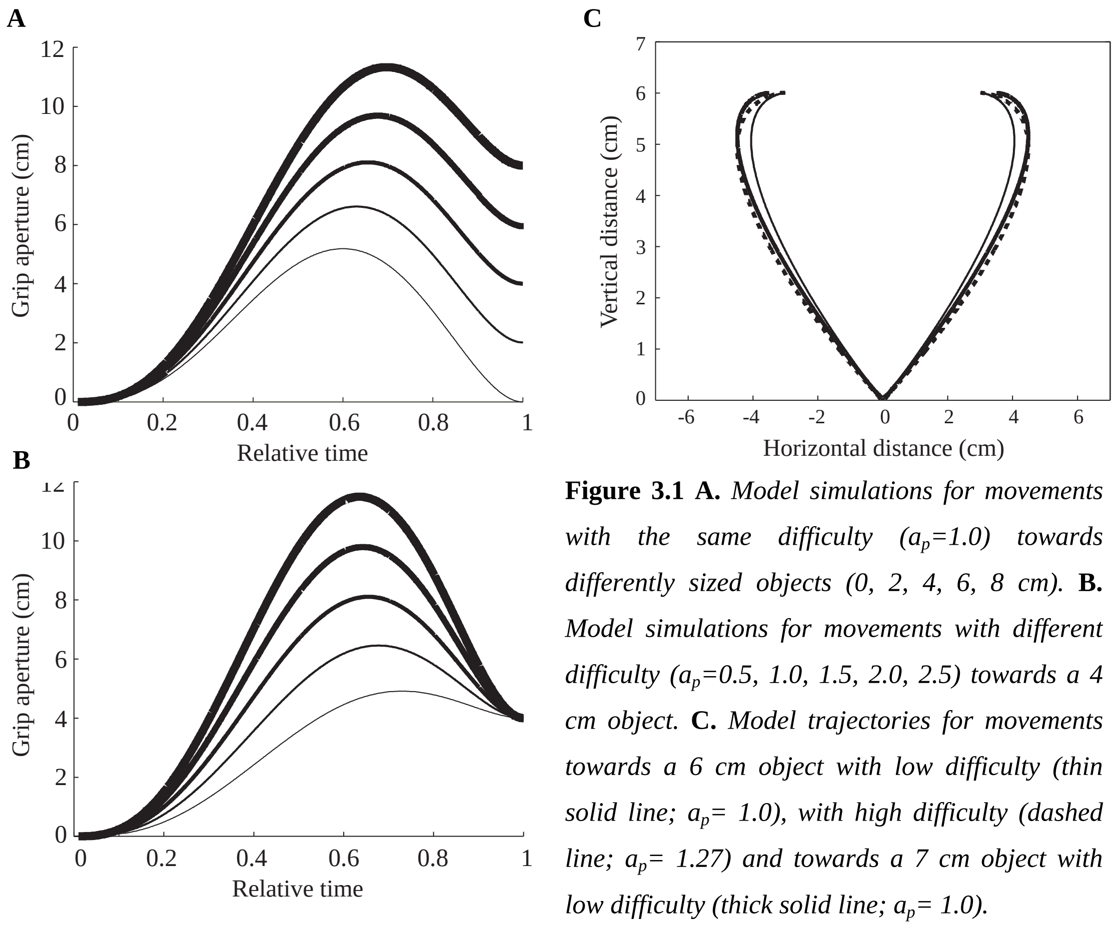

Figure 3.1 A. *Model simulations for movements with the same difficulty (a_p=1.0) towards differently sized objects (0, 2, 4, 6, 8 cm).* **B.** *Model simulations for movements with different difficulty (a_p=0.5, 1.0, 1.5, 2.0, 2.5) towards a 4 cm object.* **C.** *Model trajectories for movements towards a 6 cm object with low difficulty (thin solid line; a_p= 1.0), with high difficulty (dashed line; a_p= 1.27) and towards a 7 cm object with low difficulty (thick solid line; a_p= 1.0).*

size. Thus if misjudged estimates of size are considered when grasping such objects, the above-mentioned predictions for the timing of PGA will not necessarily hold. If the object is perceived to be larger than it really is, then the fingers will have to close further to really grasp the object. This will increase the MT and thereby reduce the relative timing of the PGA. The final velocity of grip closure will presumably be small. Conversely, if the object is perceived to be smaller than it really is, the fingers will hit the object earlier than expected. In this case, the final velocity of the grip closure will be large, MT short, and TPGA relatively late. Therefore, beside the PGA, TPGA and MT we must also take the final velocity of the grip closure into account.

We let people grasp a bar that was superimposed on the shaft of a Müller-Lyer figure. There were either inward pointing or outward pointing fins at each end. The shaft in the fins-in configuration is perceived as being shorter than the shaft in the fins-out configuration. It has been shown in various studies that this figure influences grasping movements (for an overview see table 3.1). To make sure that our findings are related to the visual information used rather than to mechanical factors, we had our subjects start their grasping movements at two different positions, completely

Table 3.1 *Effects of the Müller-Lyer illusion on perception and PGA (mm).*

Study	Perception	PGA	Real bar length
Westwood et al.(2000a)	7.85[1,*]	1.01	50,70
Westwood et al. (2000b)		1.63	50,70
Westwood et al. (2001)[3]	6.5[1,*]	2.7*	50,70
Daprati and Gentilucci (1997)	2.4[2,] 3.7[1,*]	1.0*	50,60,70
Otto-de Haart et al. (1999)[4]	9.03[1,*]	1.73	68,72,76,80
Franz et al. (2001)	2.0[2,*]	3.4*	40,43,46,49

[1]matching task.

[2] drawing task.

[3]averaged over the data of two shaft lengths given in the article

[4]only values of the binocular condition

* Significantly different from zero ($p<0.05$)

changing the orientation of the movement with respect to the bar. Beside the PGA, TPGA, MT and velocity of final grip closure we also analysed the final grip aperture (FGA).

The FGA is the distance between the markers at the time the bar was picked up. Differences in FGA between the conditions would indicate that the positions or orientations of the digits must have been different when the bars were picked up. This could be because the size was misjudged, so that the objects were not grasped as intended, or because a different grip was selected due to the judged difficulty. If illusions only influence the way we grasp by changing the visual estimate of length, then changing the starting position should make no difference to any parameter, except perhaps the MT, because the misjudged length does not depend on where the movement starts. If illusions also influence the judged difficulty, then changing the starting position could make a difference, because the digits' trajectories change in relation to the positions and orientations of the fins. In order to maximise the difference in orientation of the fins relative to the digit’s movements, we chose starting positions at the bottom and at the right side of the Müller-Lyer figure. We chose these two starting positions, rather than the top and left sides, so that the arm would not occlude the figure during the movement (our subjects were right-handed).

Methods

Subjects

This study is part of an ongoing research program that has been approved by the local ethics committee. Twelve subjects volunteered to take part in the study after being informed about what they would be required to do. They were all right-handed.

Set-up

Subjects had to grasp bars (60, 65 or 70 mm long, 5 mm wide, 3 mm high) that were placed on a projection screen. The bars were placed in such a way that their height was hardly noticeable (near-orthogonal viewing), but the subjects could clearly see that these bars were real objects. Stimuli were projected from below the screen. The resolution of the projected image was 1024x768 pixels, with one pixel corresponding with about 0.4 mm. IREDs were taped to the nails of the subject's right index finger and thumb. Positions of these IREDs were measured with a frequency of 250 Hz with an Optotrak 3020 motion recording system (resolution 0.01 mm).

Stimulus

The projected stimulus consisted of a white background with a black Müller-Lyer figure and a black dot indicating the starting position (figure 3.2A). The vertical shaft of the projected image exactly matched the size of the real bar. The length of the fins was 19.5 mm. The angles between the fins and the shaft were 30° or 150°. This resulted in two configurations of the Müller-Lyer illusion: the fins-in and the fins-out configuration. The black dot indicating the starting position had a diameter of 5mm and could either appear 15 mm beneath the proximal end of the shaft or to the right of the centre of the Müller-Lyer figure. In the latter case the distance between the centre of the Müller-Lyer figure and the starting position was equal to the length of the shaft of the Müller-Lyer figure.

We chose the distances between the starting positions and the Müller-Lyer figure in such a way that the length of the trajectory for the *index finger* was about the same when starting at the bottom and starting at the side of the figure. When starting at the bottom of the Müller-Lyer figure, the amplitude of the index finger's movement is much larger than that of the thumb. According to Fitts' law, this means that the difficulty for the movement of the index finger is much higher (Fitts 1954; Fitts and Peterson 1964). However since the speed of the hand's movement is restrained by the highest difficulty of one of the digits (Biegstraaten et al. 2003*a*) , this choice should make the MT when starting at the bottom of the figure be similar to that when starting at the side of the figure.

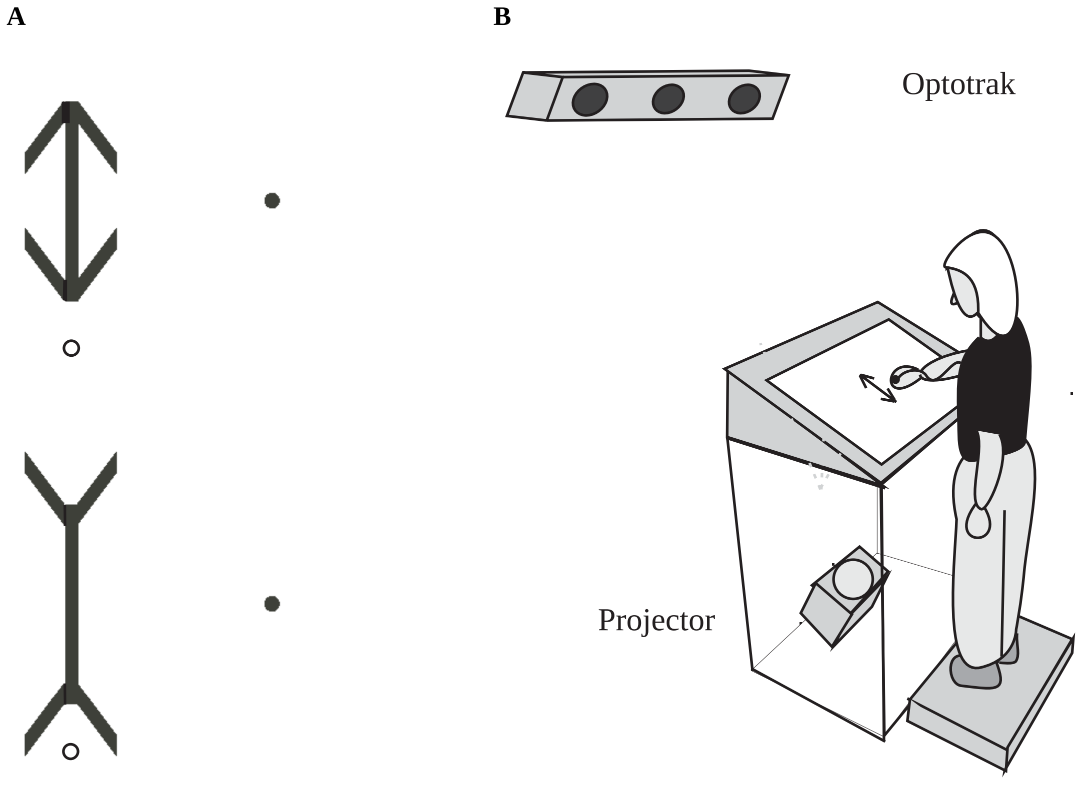

Figure 3.2 A. *Stimuli used in the experiment. The upper panel shows the fins-in configuration of the Müller-Lyer illusion; the lower panel shows the fins-out configuration. The dots represent the starting positions of the hand, either at the bottom of the Müller-Lyer figure (open symbols) or at the right side of the figure (filled symbols).* **B.** *Subjects stood behind a big screen onto which the stimuli were projected from below. Positions of the index finger and thumb were measured by an Optotrak system.*

Procedure

Subjects stood in front of the screen, with their midline aligned with the midline of the screen (figure 3.2B). Before each trial, the starting position was projected onto the screen. Subjects put their right hand at the starting point with the tip of their index finger and thumb touching each other. Then subjects closed their eyes, after which the stimulus was projected and the experimenter placed the bar exactly on the shaft of the projected Müller-Lyer figure. The experimenter then gave a verbal signal, following which the subject opened his/her eyes, grasped the bar and placed it at the bottom of the screen. This procedure was repeated for every trial. The experiment consisted of 12 conditions (3 bar lengths, 2 configurations and 2 starting positions) that were each repeated 10 times, resulting in 120 trials per subject, in random order.

Data analysis

For each frame the velocity was computed from a local fit to 7 position samples of the IREDs (for the exact method see Biegstraaten et al. 2003*b*). Because of the rather small movement amplitude of the thumb when the starting position was below the figure, the beginning and end of the grasping movement were based on the tangential velocity of the index finger. The onset of the movement was defined as the last frame before peak velocity in which the velocity was smaller than that on the preceding frame. The offset was defined as the first frame after peak velocity in which the velocity was smaller than that on the following frame (for a discussion about determining movement onsets and offsets also see Biegstraaten et al. 2003*b*). The MT was calculated as the time between onset and offset of the movement. To check whether the determined offset of the movement was a valid one, we also determined the height of the trajectory around movement offset. The FGA was defined as the absolute distance between index finger and thumb at movement offset. Peak grip aperture (PGA) was defined as the maximum absolute distance between index finger and thumb during the movement.

Statistical tests were conducted across subjects. Data were analysed with repeated measures ANOVA's with the factors bar length (60, 65, 70 mm), configuration (inward pointing fins, outward pointing fins) and starting position (below, right). Dependent variables were: PGA, MT, FGA and percentage TPGA. Values are presented as the mean ± standard errors between subjects. A significance level of α=0.05 was used for all statistical analyses.

Results

Figure 3.3 shows the average grip aperture (upper panels) and the average height of the trajectory of the index finger and thumb (lower panels) as a function of relative time for each configuration of the illusory figure. Note that the digits are at their lowest points at movement offset (100% MT), after which they presumably start to lift the bar. The PGA was larger and earlier for the fins-out configuration (dashed lines). This will be discussed in more detail below. The bar length did not influence the maximum height of the trajectory of the thumb or index finger, but subjects lifted their thumb significantly higher for the fins-out configuration than for the fins-in configuration (19.2 ± 6.3 mm and 17.3 ± 6.8 mm respectively; $p=0.03$). Subjects also lifted their index finger higher when starting at the bottom of the Müller-Lyer figure than when starting at the side of the Müller-Lyer figure (31.1 ± 9.1 mm and 25.1 ± 6.4 mm, respectively; $p<0.0001$).

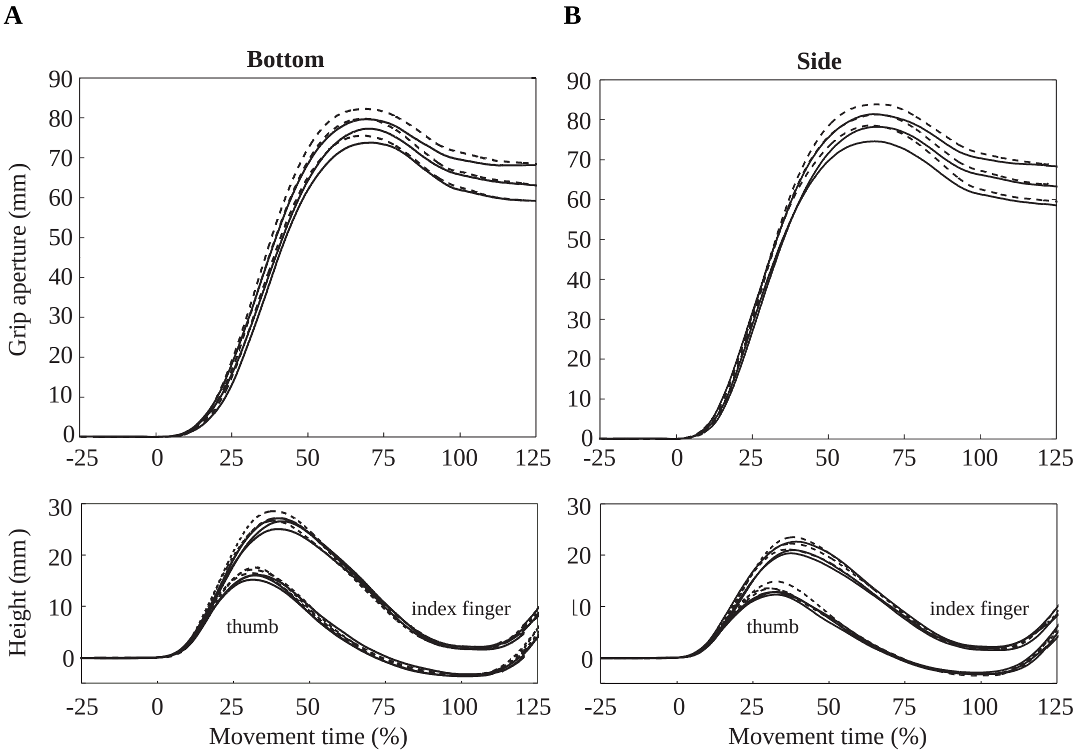

Figure 3.3 *The average grip aperture (upper panels) and height of the trajectory (lower panels) as a function of the time relative to the movement.* **A.** *Movements starting at the bottom of the Müller-Lyer figure.* **B.** *Movements starting at the side of the Müller-Lyer figure. Dashed lines represent movements towards the fins-out configuration of the Müller-Lyer figure. Solid lines represent movements towards the fins-in configuration of the Müller-Lyer figure. The 3 lines represent the three real bar sizes.*

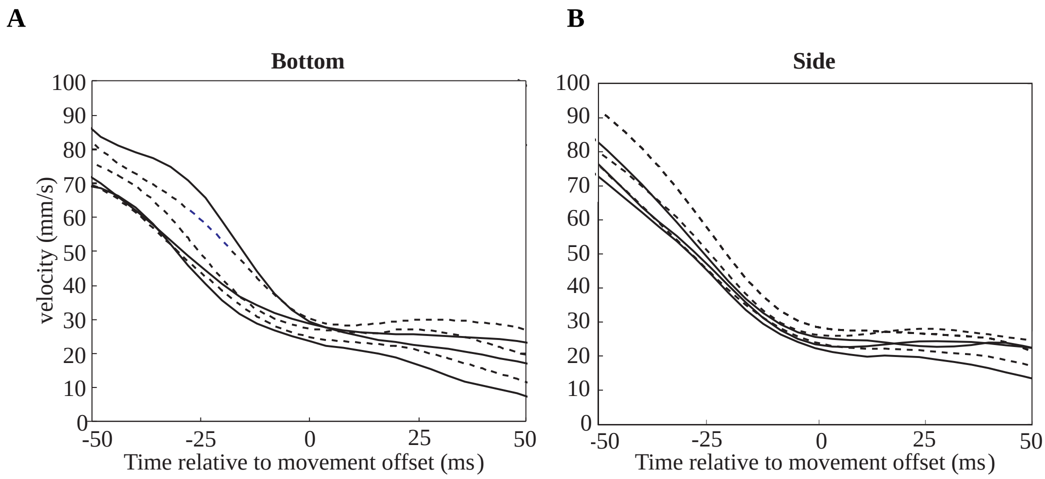

Figure 3.4. *The average velocity of grip closure near movement offset.* **A.** *Movements starting at the bottom of the Müller-Lyer figure.* **B.** *Movements starting at the side of the Müller-Lyer figure. Dashed lines represent movements towards the fins-out configuration of the Müller-Lyer figure. Solid lines represent movements towards the fins-in configuration of the Müller-Lyer figure. The 3 lines represent the three real bar sizes.*

Figure 3.4 shows the velocity of the grip closure around movement offset. Before movement offset there was a sharp decrease in velocity. After movement offset the grip continued to close at a constant rate, presumably because the thumb reached the object later than the finger on some trials, and due to skin compression as the grip force is increased. This pattern was independent of the condition. The velocity at movement offset did not differ between configurations or starting positions.

Movement times were longer for the fins-out configuration (726 ± 23 ms) than for the fins in configuration (708 ± 23 ms; $p=0.01$; figure 3.5a). Movement times also differed between starting positions (729 ms ± 22 and 705 ± 23 ms, for movements starting from beneath and beside the figure, respectively; $p<0.05$) and bar lengths (706 ±27 ms, 719 ± 30 ms, 725 ±27 ms for 60 mm, 65 mm and 70 mm, respectively; $p<0.05$). There was no significant interaction between starting position and configuration. The longer MT for movements starting from beneath the figure could be due to the slightly longer distance that the finger has to move.

Figure 3.5B shows the PGA for each condition. PGA differed significantly between bar lengths ($p<0.001$), configurations ($p=0.0017$) and starting positions ($p=0.0196$). There were no significant interactions between the factors. An increase of actual object length by 10 mm led to an increase of PGA by about 6 mm, which is within the range of values found in other studies. The difference in PGA between the fins-out configuration and the fins-in configuration was 3.6 mm. This is slightly larger than the effects found in other studies using the Müller-Lyer illusion (see table 3.1). When starting from the right side of the figure, the PGA was 2.1 mm larger than when starting from the bottom of the figure.

The TPGA was significantly smaller (relative timing of PGA earlier) for the fins-out configuration (i.e. when PGA was larger) than for the fins-in configuration (67 ± 0.7 % and 68 ± 0.7 % of the MT, respectively; $p<0.05$; figure 3.5C). The TPGA was larger for movements from below the figure than from ones starting from the side (69 ± 0.8 % and 66 ± 0.6%, respectively; $p=0.06$). There were no significant interactions.

The FGA was influenced by the length of the bars ($p<0.01$; gain = 0.8) and by the configuration ($p=0.03$; figure 3.5D). In the fins-out configuration the FGA was 1.4 mm larger than in the fins-in configuration. These differences are presumably caused by changes in the distance between the IRED and the point of contact with the object, because a different part of the digit makes the contact, or because the orientation of the digit is different at the time of contact, or both. The subjects also must have grasped the objects differently for the different real lengths, because the gain was only 0.8. The difference related to the configuration only disappeared after the bar was raised (see figure 3.3). The FGA did not depend on the starting position ($p=0.94$).

Discussion

Beside effects of the configuration, we also found an effect of the starting position on the PGA, the relative timing of the PGA and the MT. Movements starting at the bottom of the Müller-Lyer figure were slower than movements starting at the right side of the figure. At the same time the PGA was smaller and occurred later during the movement. An influence of the starting position on PGA is obviously inconsistent with the grip aperture only depending on the perceived size. This trade-off between MT and PGA could mean that the difficulty of the grasping movement was estimated to be similar for both starting positions. The same difficulty can give rise to a long MT (perhaps because of an increase in distance) with a small PGA relatively late in the movement (lower a_p) or to a short MT with a large PGA relatively early in the

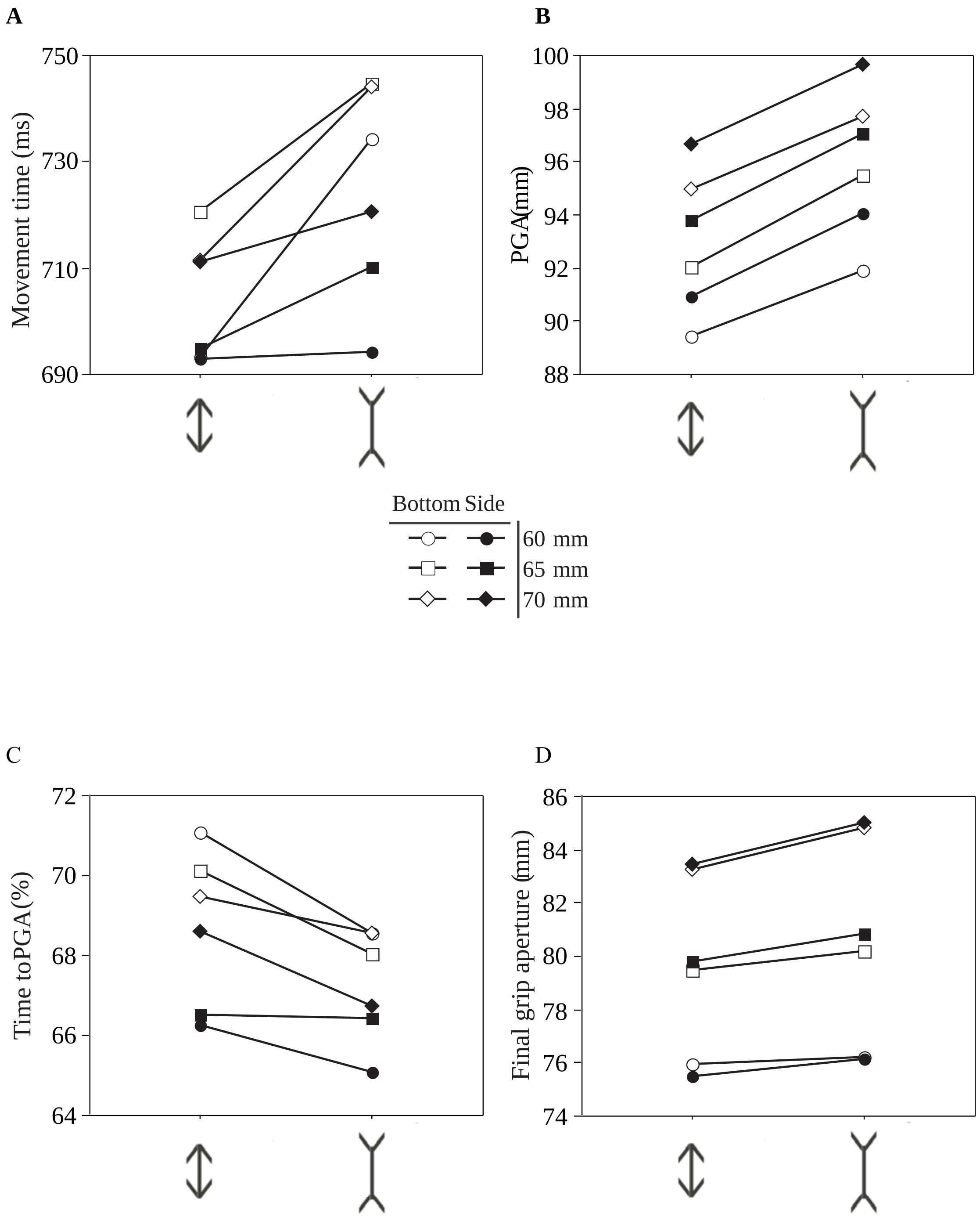

Figure 3.5 *Mean MT (***A***), PGA (***B***), TPGA (***C***) and FGA (***D***). Open symbols represent movements that started at the bottom of the Müller-Lyer figure. Solid symbols represent movements that started at the right side of the figure. Bar lengths were 60 mm (circles), 65 mm (squares) and 70 mm (diamonds).*

movement (larger a_p). Thus the pattern of results that we found for the two starting positions can be consistent with an explanation in terms of judged difficulty. Note that unlike for movements from below (rather than the right), the smaller PGA later in the movement for the fins-in configuration (compared to the fins-out configuration) occurs in combination with a shorter (rather than a longer) MT.

Movements towards the fins-out configuration are both *slower* than the movements towards the fins-in configuration and the PGA is *larger* and occurs *earlier* in time. All three effects are consistent with judging the fins-out configuration to be more difficult (see figure 3.1B). However, both a longer MT and a larger PGA were also found for larger targets, so it may not be surprising to also find them for targets that only look larger. The most important argument against illusory size alone being responsible for our findings is the influence of the illusion on the TPGA. No corresponding influence was found for the real change in size, and if anything, the trend is even in the opposite direction.

In the introduction we mentioned that effects on MT and TPGA could also be caused by a mismatch between the judged and actual positions of the object's surface. We predicted that if size were misjudged then movements for the fins-in configuration (solid lines) would be faster than normal near the calculated movement offset, because the digits contacted the object earlier than was anticipated. We would expect movements for the fins-out configuration (dashed lines) to be slower than normal just before the calculated movement offset, because the digits will have slowed down considerably before reaching the object since they were expected to contact the object earlier due to the larger apparent size. This is clearly not what we found (figure 3.4). Thus the Müller-Lyer illusion cannot only influence grasping through its influence on perceived size.

Beside the timing, the illusion also influenced several other parameters that appear to be unrelated to the perceived size. Subjects also lift their thumb higher for the fins-out configuration (figure 3.3) and grasp the bar differently (figure 3.5D). The difference in FGA suggests that the configuration of the hand was different when it contacted the objects. This could result from misjudging the length of the bar, and therefore where the digits will contact the object. However, the higher maximal height of the digits in the fins-out configuration cannot be related to the judged length because the real bar length had no effect. Taken all findings together, we think that subjects purposely chose a different hand configuration for the two fin configurations because they judged the fins-out configuration to be more difficult.

The results are difficult to reconcile with the view that the illusion only influences our actions through the changed judgements of size. However our data do not exclude the possibility that performance is influenced by visual estimates of position and length (De Grave et al. 2003) as well as of the difficulty. We conclude that the Müller-Lyer illusion can change people's movement strategy in a manner that is unrelated to the spatial attributes that the illusion is supposed to change (length). This is unfortunate because it will interfere with the use of illusions as a tool for studying the information that is used for motor tasks.

Chapter 4

Impact forces cannot explain the one-target advantage in rapid aimed hand movements

We thank Jos Adam for his useful suggestions regarding the set-up of the experiment

Abstract

A pointing movement is executed faster when a subject is allowed to stop at the first target than when the subject has to proceed to a second target ("one-target advantage"). Our hypothesis was that this is because the impact at the target helps to stop the finger when the finger does not have to proceed to a second target. This hypothesis would predict that the horizontal force at contact with the first target should be larger when there is only one-target. Modelling smooth movements with larger forces at contact using a minimum jerk model, shows that the peak velocity is slightly higher and it occurs later during the movement when there is only one-target. Although the one-target advantage was present in our experiment, the horizontal force at contact in the one-target condition was not larger then in the two-target condition. The time of the maximum velocity did not differ, but the maximum velocity was higher in the one-target condition. Thus our hypothesis is rejected, favouring a non-mechanical explanation of the one-target advantage.

Introduction

Numerous studies have reported that a rapid aimed hand movement to a target is executed faster if the hand is allowed to stop at the target, than if it has to proceed to a second target (Adam et al., 2000; Chamberlin & Magill, 1989; Christina et al., 1985; Fischman, 1984; Fischman & Reeve, 1992; Sidaway, 1991). This so-called one-target advantage occurs regardless of the distance to be moved (either to the first target or to the second target; Adam et al., 2000), the direction of the second movement (except a reversal movement; Adam et al., 2000; Fischman, 1984), the number of targets (Smiley-Oyen & Worringham, 2001; Fischman, 1984) or the kind of movement (abduction or adduction; Helsen et al., 2001). It is independent of eye movements (Adam et al., 2000) and remains constant over practice (Adam et al., 2001). The effect is about 8%-15% of the movement time.

Understanding why the one-target advantage arises is not so easy. Several explanations exist. The one-target advantage has been explained by the need to prepare the second movement during execution of the first movement (Chamberlin & Magill,1989), the need to have a more controlled first movement in order to execute the second one accurately (Fischman & Reeve, 1992) or a combination of both (Adam et al., 2000).

We propose another explanation, the *deceleration hypothesis*. This explanation is based on the notion that impact with the target is an important factor in the deceleration of the arm in single element aiming movements (Teasdale & Schmidt, 1991). Impact with the target leads to a force opposite to the direction of the movement and thus to deceleration of the hand. This means that less muscular force is needed for the same deceleration. This could influence the way in which the movements are controlled. When high velocities at impact are not a problem, impact with the target could passively provide a part of the deceleration, so that the same muscular forces yield a shorter deceleration time.

There is indeed some evidence that impact can influence movement characteristics. For instance, in the study of Adam et al. (1993) subjects had to slide a pen over a tablet to a target and either stop there, or return to the starting position. In both cases there were conditions with and without a mechanical stop at the target. Shorter movement time, higher peak velocity and lower percentage of the movement time spent decelerating (all to small targets) were found when subjects could use a mechanical stop at the target. This indicates that passive deceleration can indeed induce faster movements.

Adam et al. (1993, 1997) already suggested that passive deceleration, and thus large impact forces at initial contact with the first target in the one-target condition, could account for the one-target advantage in rapid aimed hand movements. In the two-target condition, large impact forces opposite to the movement direction are disadvantageous because they hinder the departure from the first target. Therefore subjects are more likely to actively slow down their movement to the first target.

This proposal can explain why the one-target advantage is not found for reversal movements (Adam et al., 1993; Lajoie & Franks, 1997), because the reaction force is in the same direction as the reversal movement so that the kinetic energy stored in deformation of the skin and of finger muscles can even be used to start the reversal movement (Guiard, 1993). When there is no second movement, the reaction force at the first target may cause the finger to bounce back a little towards the starting position, so there are limitations to its magnitude, perhaps explaining why subjects can be even faster for reversal movements (Lajoie & Franks, 1997).

Adam et al. (1997) tested the *deceleration hypothesis* by measuring the vertical impact force in a one-target condition and a two-target condition. They did not find differences in vertical impact force between the conditions, and therefore rejected the hypothesis. However their experiment is not the best test of the hypothesis based on the hypothesis of Adam et al (1993), as the latter involved horizontal forces, whereas the 1997 experiment only measured vertical forces.

Could it be that it is not the vertical force, as measured by Adam et al. (1997), but the horizontal force (in the main direction of the movement) that is different for a one-target and a two-target condition? To determine whether this *deceleration hypothesis* could explain the one-target advantage we first investigated the consequences of having a different horizontal force at contact by changing the final deceleration in a minimum-jerk model for pointing (Flash & Hogan, 1985). We found that changes in the final deceleration could influence the movement time. We therefore had subjects perform one-target and two-target movements and measured the horizontal force at contact with the first target. However, measuring the deceleration and force at the end of the movement is difficult, because it depends on the details of how contact is made. We therefore also used the above-mentioned minimum-jerk model to predict the values of related kinematic measures that could be tested more easily. We did this for the *deceleration hypothesis* and for an *alternative hypothesis* in which a general increase in *speed* is responsible for the one-target advantage (Chamberlin & Magill, 1989; Fischman & Reeve, 1992 and Adam et al., 2000). We compared the predicted values for both hypotheses with the experimental results.

Model for pointing

The minimum-jerk pointing model of Flash & Hogan (1985) describes a pointing movement with constraints at the beginning and the end of the movement. For a point-to-point movement the parameters are movement time, the initial and final positions of the finger, and a velocity and deceleration of zero at both the beginning and the end of the movement. Smeets & Brenner (1999) adapted this model with a non-zero deceleration at the end of the movement, and scaled that by the squared movement time to get an "approach parameter". The horizontal component of a pointing movement is then described as follows:

$$x(t_r) = \left(\tfrac{1}{2} a_p (t_r - 1)^2 + l(6t_r^2 - 15t_r + 10)\right) t_r^3$$

where t_r is the relative time, *l* the horizontal distance between the targets, and a_p the approach parameter: the final deceleration scaled with the squared movement time. We define the end of simulated the movement as the time the velocity is zero. We model three different movements: the two-target condition (same for both hypotheses), the impact condition (one-target condition according to the *deceleration hypothesis*) and the no-impact condition; the one target condition according to the alternative hypothesis ("*speed hypothesis*") that a general increase in speed (rather than a change in final deceleration) is responsible for the one-target advantage. For the two-target condition acceleration at contact should be zero, because the finger decelerates before contact and accelerates after contact. By its definition the no-impact condition also requires a zero acceleration at contact. We therefore used an approach parameter of zero at the end of the movement to the first target for these two conditions. In the impact condition on the other hand, it is indefinite what should happen after contact, so any final acceleration is possible.

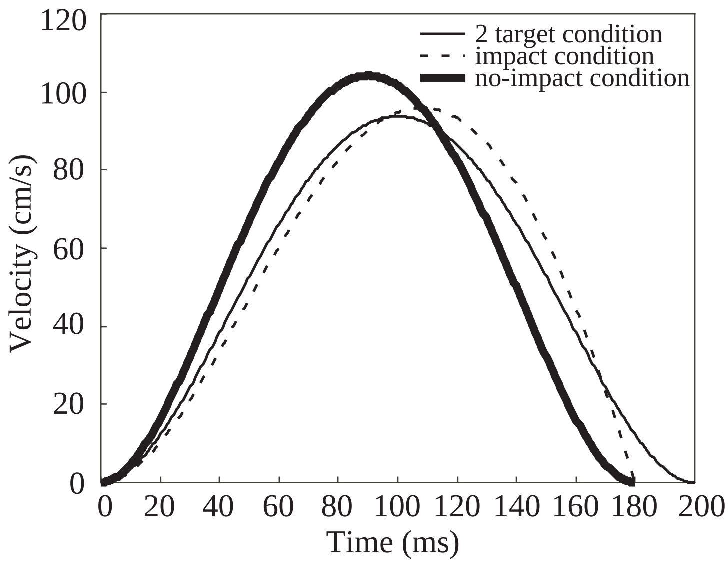

Figure 4.1 *Model predictions. The thin black line shows the horizontal velocity profile for the two-target condition as predicted by the minimum-jerk pointing model. The dashed line shows the predictions for the one-target condition according to the deceleration hypothesis (impact condition). The thick black line shows the predictions for the one-target condition according to the speed hypothesis (no-impact condition).*

To simulate our movements we used a one-target advantage of 10%. This is a moderate effect based on the percentages that were found in previous studies (table 1 Adam et al. 2000). For a given MT and *l* we can calculate the peak velocity and the time of peak velocity when a_p=0 (two-target condition, no-impact condition) as well as for any other value of a_p (impact condition). Thus we can predict the influence of any reduction in movement time and any value of a_p on the magnitude of peak velocity and its timing.

For the two-target condition and the no-impact condition the velocity and the acceleration at contact are always zero. Peak velocity is reached at 50% of the movement. The peak velocity is directly related to the movement time. The model predicts that for 10% less MT, the peak velocity in the no-impact condition will be 11% larger (see figure 4.1).

For the impact condition, the prediction depends on the value of a_p. Increasing a_p results in a slightly higher peak velocity that is reached later (at up to 60 % of the movement time rather than at 50% as in the two-target condition and in the no-impact condition). The maximal effect of impact is found for a_p=8*l*. In that case and a one-target advantage of 10% the peak velocity increases slightly by 2.4% (see figure 4.1).

Having determined several kinematic parameters that would indicate whether an increase in the final deceleration or a general increase in speed accounts for the one-target advantage, we are ready to test our hypothesis experimentally. We let subjects tap one-target with their index finger and either stop there or move on to a second target. We measured the movement of the finger and all components of the forces during contact with the first target.

Experimental methods

This study is part of an ongoing research program that has been approved by the local ethics committee. 10 Subjects volunteered to take part in the study after being informed about what they would be required to do.

Set-up

The set up consisted of a force sensor (ATI, Nano17 Ft) and two black plastic cylinders (starting target and second target) mounted on a wooden board such that the total surface was flat. The cylinders were the same size as the force sensor (17 mm diameter, 14.5 mm height). The starting position was the rightmost cylinder. The first target (force sensor) was located 10 cm to the left of the starting position. The second target (plastic cylinder) was located 10 cm to the left of the first target (figure 4.2). Subjects sat with their midline aligned with the position of the second target.

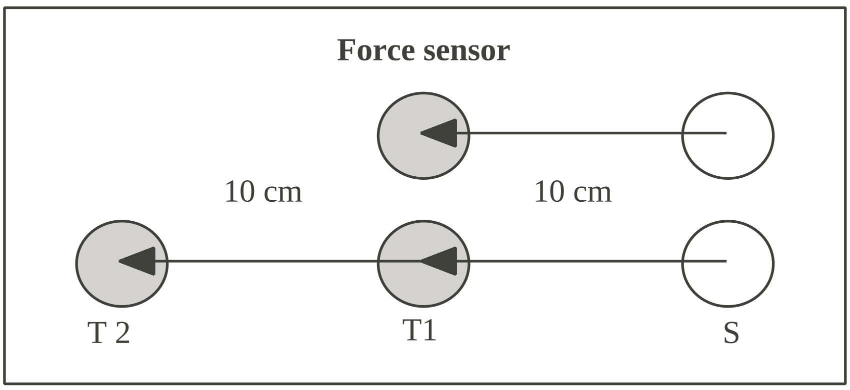

Figure 4.2 *Experimental set-up. Subjects moved their index finger from the starting point (S) to the first target (T1) and either stopped there (one-target condition) or moved on to the second target (T2, two-target condition).*

An IRED was placed on the nail of the subject's right index finger. Positions of this IRED were measured at 500 Hz with the Optotrak motion recording system (resolution 0.01 mm). The force and torque at the first target were measured in all three directions by the force sensor (resolution 0.025 N) at a sampling rate of 500 Hz.

The force sensor data were measured in synchrony with the movement data by means of the Optotrak Data Acquisition Unit. We determined the delay of the signal processing of the force sensor to be 8 ms, and corrected the data afterwards.

Procedure

Subjects were instructed to place their right index finger on the starting position. All movements were made from right to left. There were two different conditions, each performed in a separate block. After an auditory signal subjects had to move their index finger to the first target and either stop there (one-target condition), or strike it and move on to the second target (two-target condition). Emphasis was placed on executing the movement as fast as possible. They had to remain on the final target until a second auditory signal sounded.

To reduce errors, the experimenter removed the second target from the board in the one-target condition. Subjects performed 15 practice trials before performing a block of 20 test trials in each condition. The presentation order of conditions was counterbalanced between subjects.

Data analysis

When subjects contact the target at its edge, the mechanics of making contact are different: the side instead of the surface of the target decelerates the finger. As we cannot measure this force, we had to exclude such trials. To do so, we calculated the points of force application for each trial from the measured forces and torques. Trials in which these points were within 1.5 mm of the edge of the target (3.4 % of all trials) were removed from analysis. Trials in which the MT was more than two standard deviations above or below the mean for that subject and condition were also removed from further analysis. This resulted in removal of approximately 3.8% of the remaining trials. The data of one subject had to be removed from the analysis, because he reached the maximum of the range of the force sensor.

Only the movements to the first target were analysed. Instantaneous velocity and acceleration were computed from position samples of the IRED's. To do so we fit a second order polynomial to 7 position samples (12 ms window) around each position. Based on three parameters of the fit polynomial we can estimate the finger's position, velocity and acceleration at that instant. This is a convenient method for combining data smoothing and differentiation in a single procedure (Smeets et al., 2002). The advantage of this method over conventional filtering is that it does not yield overshoots near a sharp change in velocity (such as the impact with the target). This advantage is illustrated in figure 4.3.

The beginning and end of the movement to the first target were based on the tangential velocity. The onset of the movement was defined as the last frame before peak velocity in which the velocity was smaller than that on the preceding frame. The offset was defined as the first frame after peak velocity in which the velocity was smaller than that on the following frame. We could not use a velocity threshold because subjects were not required to (and indeed did not) stop completely at the first target in the two-target condition. This method is insensitive to the impact itself. In figure 4.4 the difference between both methods of determining the onset and offset of

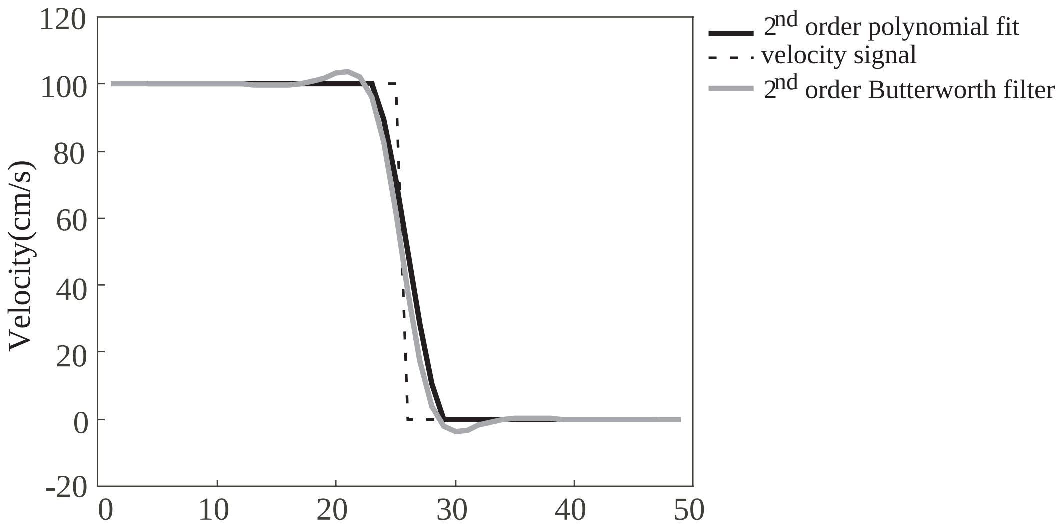

Figure 4.3. *Comparison between our smoothing for the determination of velocity and the use of a second-order-dual pass Butterworth filter. Using a Butterworth filter (grey line) with a cut-off frequency of 35 Hz induces overshoots near sharp edges in the velocity profile. Using a second order polynomial fit with a 12 ms moving window (black line) does not introduce such overshoots. The dashed line denotes the modelled velocity signal.*

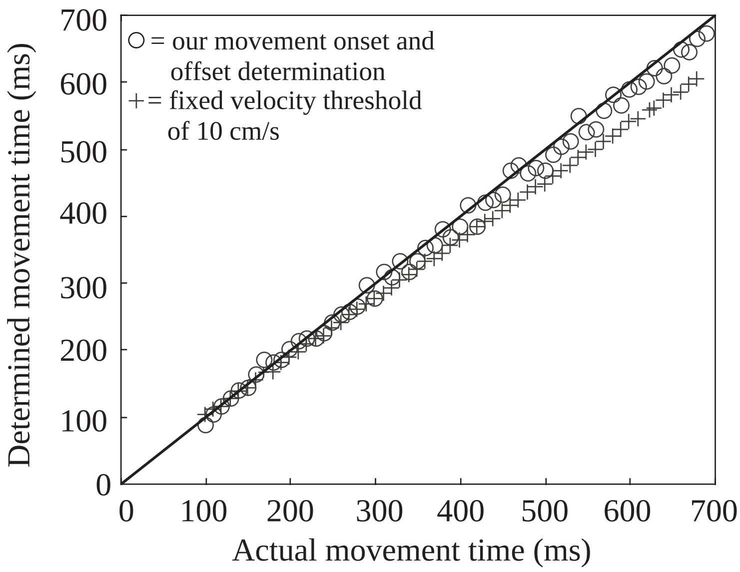

Figure 4.4. *Comparison between our determination of movement onset and offset (see method section; open circles) and that when a fixed velocity threshold (10 cm/s; crosses) is used. The unity line indicates the actual (simulated) movement time. The modelled trajectories were 10 cm minimum-jerk movements with noise.*

the movement are shown. When using an fixed velocity threshold, with longer movement durations, the detected movement times deviate more from the actual movement time.

The MT (time between onset and offset of the movement), the travelled horizontal distance and the maximum height of the trajectory of the finger were determined for each trial. Traces of the horizontal impact forces at the first target were averaged as a function of time after being synchronised with respect to the movement offset. Velocity traces were averaged as a function of relative time. This relative time was subsequently multiplied with the average movement time.

A repeated measures ANOVA was used to test the difference between MT, peak velocity and time of peak velocity in the one-target and in the two-target condition.

Results

Movement time

There was a significantly shorter MT in the one-target condition (176 ms) than in the two-target condition (193 ms, figure 4.5A), The 17 ms (8.8%) one-target advantage was similar to values found in other studies (for an overview see Adam et al., 2000), and close to the 10% we assumed in our model calculations.

Distance

The travelled horizontal distance was 106 mm in both conditions. The maximum height of the trajectory was about 28 mm. These values were not statistically different between conditions.

Velocity

Peak horizontal velocity was significantly higher for the one-target condition than for the two-target condition (figure 4.5B). The timing of the peak velocity occurred at 60% of the movement time (figure 4.5C) and did not differ between the conditions ($p=0.18$). Figure 4.5D shows the average velocity traces, synchronised at movement onset.

Force

The horizontal force around movement offset is shown in figure 4.5E. Horizontal and vertical impact forces did not differ between conditions ($F_x=1.25$ N, $p=0.12$; $F_z=3.67$ N, $p=0.36$). This is inconsistent with the *deceleration hypothesis*.

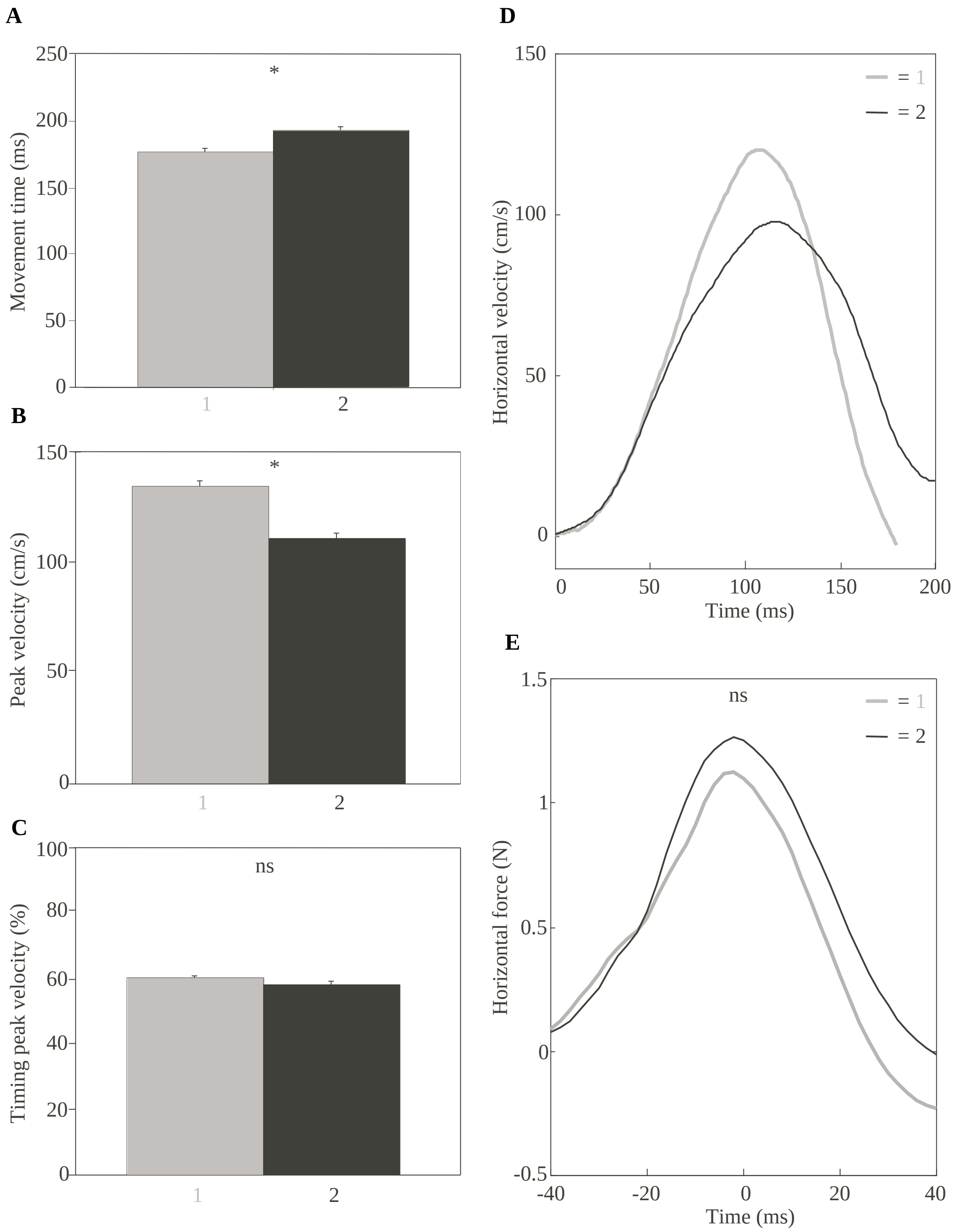

Figure 4.5 *Mean values of MT (***A***), peak horizontal velocity (***B***) and relative time of peak velocity (***C***) for the one-target condition (grey bars) and the two-target condition (black bars). *=p<0.05.* **D***: The average horizontal velocity as a function of the average time relative to movement onset.* **E***: The horizontal force, averaged relative to the time of the end of the movement for the two conditions. Positive values represent forces applied in the direction of the main movement (leftward). Note that due to the averaging process, the peak of the average velocity traces in* ***D*** *are slightly lower than the averages of the peak velocities in* ***B***.

Discussion

We hypothesised that the one-target advantage could be explained by a difference in deceleration at impact: in the one-target condition we expected deceleration to be larger than in the two-target condition. According to our model for the *deceleration hypothesis* a larger deceleration at the target (a larger a_p) will give rise to a later timing of the peak velocity. The alternative *speed hypothesis* predicts that peak velocity will be higher in the one-target condition than in the two-target condition, and will be reached at the same relative time. Moreover, the final deceleration should be zero for both conditions.

We reproduced the one-target advantage in our experiment. However, we did not find a higher impact force for the one-target condition than for the two-target condition (even a trend in the opposite direction!), which is opposite to the fundamental prediction for the *deceleration hypothesis*. The peak velocity was significantly higher in the one-target condition than in the two-target condition and was reached earlier in absolute time (see figure 4.5D). Both results are consistent with the *speed hypothesis* model. The timing of peak velocity did not differ between the conditions, but peak velocity was not reached at 50% of the movement time as predicted by the *speed hypothesis*, but at 60%.

From figure 4.5D it can be seen that there is a difference in final deceleration (the slope of the velocity curve at its end) between the conditions. The final deceleration in the two-target condition is close to zero, while the final deceleration in the one-target condition is much larger. This is what we had predicted, but the reason for this cannot be as assumed for our prediction because the impact force does not show a corresponding effect. The higher final velocity in the two-target condition presumably has a similar effect as the non-zero final deceleration in the one-target condition on the timing of the peak velocity. To account for the combination of less deceleration of the finger at the time of contact and yet a larger impact force in the two-target condition, we have to conclude that the impact force in the two-target condition does not decelerate the finger. Instead it may primarily deform the skin during contact, which is less inconsistent with the high velocity during contact with the first target in the two-target condition.

The timing of peak velocity always seems to follow the prediction of the *deceleration hypothesis* for the one-target condition: a peak at 60% of the movement time. Therefore we conclude that impact force influences the velocity profile in both conditions. However, the one-target advantage cannot be explained by a *difference* in impact force. Neither a larger impact force nor the kinematic changes that are predicted by the *deceleration hypothesis* were found experimentally. Thus our hypothesis is rejected, favouring a non-mechanical explanation of the one-target advantage.

Chapter 5

The relation between force and movement when grasping an object with a precision grip.

Abstract

When picking up an object, grip and lift forces are coordinated to prevent the object from slipping without exerting excessively large forces. The ratio between these forces depends on how slippery the grasp surface is. When reaching out for the object, the digits approach its surface on curved paths that end perpendicular to the surface at the positions of contact. This minimizes the effect of spatial variability on the final accuracy, and ensures that the forces exerted at contact are nearly perpendicular to the surface, so that friction will prevent the digits from slipping. The necessary overlap between the final direction of the reaching movement and the direction of the force applied to the surface of the object in order to pick it up, suggests that the two may be directly related. Is this indeed the case?

We let subject grasp a cube from three different starting positions. We found no direct relationship between the control of the reaching movement towards the object and the force applied at the surface of the object. On the contrary, the impact force was low, and the digits spent more than 100 ms building up the grip force while in contact with the surface of the cube. We conclude that the reaching and lifting movements are quite independent.

Introduction

We reach and grasp objects many times a day. Most of the time, we can perform this task very well and it does not seem very complex. However, in fact it is. We have to identify the object, to locate appropriate grasp positions on the surfaces of the object and move the digits to these points. When we have positioned our digits on the surface, we must exert forces is such a way that we can lift the object in a stable manner and use it for a particular goal. What is the relation between the positioning of the digits and the control of the forces?

Many studies have focused on the interaction between the digits and the contact surfaces of the object from the moment the object is contacted until the object is released again (Edin et al. 1992; Gordon et al. 1993; Johansson and Westling 1984; Kinoshita et al. 1997; Westling and Johansson 1984). Grasp stability is mainly ensured by controlling the ratio between lift forces (along the grasp surface) and grip forces (orthogonal to the surface; Reilmann et al. 2001; Westling and Johansson 1984). Coordinating grip forces and lift forces prevents the digits from slipping over the surfaces of the object without having to exert excessively large forces. The ratio between grip force and lift force depends on the frictional conditions of the grasp surface. A slippery object (for instance silk) requires a larger ratio than an object with a rough surface (sandpaper; Fagergren et al. 2003, Johansson and Westling 1984). The ratio between grip force and lift force during the lift phase is not determined for the whole grip but is controlled independently for each digit (Burstedt et al. 1999; Burstedt et al. 1997; Edin et al. 1992). Thus subjects appear to control the direction of each digit's force very accurately.

Smeets and Brenner (1999) have shown that the characteristic grip preshaping while reaching for an object can be understood as the result of the digits moving more or less independently towards their designated places of contact on the surface of the object. Obviously the digits cannot move completely independently, because they are anatomically linked. However, experiments have shown that anatomical constraints do not have much influence on grasping (Flanagan and Tresilian 1994; Smeets and Brenner 2001). Thus, both the reach to grasp movement and the build-up of the grasp forces are the result of independent control of the digits.

If you want to be able to lift the object, both digits should arrive simultaneously at opposite sides of the object. Each digit's path is also influenced by a number of additional requirements. In order to make contact at the correct position it is advantageous to approach the surface more or less orthogonally (Smeets and Brenner 1999). The extent to which each digit will tend to approach perpendicularly depends on the surface. If accurate localization is needed, for example because the surface is slippery, the approach will be more perpendicular. Slippery surfaces also requires a larger ratio between grip and lift forces, so there is some correspondence between the required movement before contact and the required direction of the force after contact is made with the object. Another example is a fragile object, which constrains the grip forces to be rather low. It is known that one approaches an object that looks fragile with more care than one that looks very robust (Marteniuk et al. 1987; Savelsbergh et al. 1996).

Is the correspondence between the requirements for reading and lifting reflected in the transition between the two, perhaps simplifying the control of the combined action? In order to find out, we examined how the force changes after the moment of initial contact and whether this is related to how the object is approached. We varied the movement constraints by letting the subjects start their movements from different locations. We did not change the force constraints. Further, we analysed in detail how the movements of the digits and their exerted forces change after the digits contacted the surface.

Methods

This study is part of an ongoing research program that has been approved by the local ethics committee. Nine subjects volunteered to take part in the study after being informed about what they would be required to do.

Set up

The cube that subjects had to lift was 5 cm high, 5 cm wide and 5 cm deep (figure 5.1A). It had two grip surfaces that were covered with sandpaper to prevent the skin from slipping over the surface, because such slipping would make the interpretation of the data more complicated. Inside the cube, the grip surfaces were each attached to a force sensor (ATI, Nano17 Ft). Each grip surface weighed 11gr, the whole cube weighed 350 gr. The force (resolution 0.025 N) and torque (resolution 0.0625 Nmm) at the grasp surfaces were measured at a sampling rate of 500 Hz in all three directions. Two IRED's were placed on top of the cube to measure the position of the cube. IRED's were also placed on the nails of the subject's right index finger and thumb. Positions of these IRED's were measured at 500 Hz with the Optotrak motion recording system (resolution 0.01 mm). The force sensor data were measured in synchrony with the movement data by means of the Optotrak Data Acquisition Unit. We determined the delay of the signal processing of the force sensor to be 8 ms, and corrected for this.

Subjects sat with the cube located directly in front of their right shoulder. They had to start their grasping movement from one of three starting positions (figure 5.1B). All starting positions were 15 cm from the cube. Starting positions were in front (1), to the front-right (2) and to the right of the cube (3). A 3 cm high plateau, onto which the subjects had to place the cube, was located 2.5 cm behind the far edge of the cube.

Procedure

Before participating subjects washed their hands with soap and water, to remove excessive oil and fat from the skin. Since the felt weight and surface texture on the previous trial may be used to plan each trial (Westling and Johansson 1984), we let subjects grasp the cube five times before beginning with the experiment. The weight and surface texture were constant throughout our study.

Subjects put their right hand at one of the starting positions with the tip of their index finger and thumb touching each other. The experimenter gave a verbal signal in response to which the subject grasped the cube and placed it on the plateau. No instructions were given about the speed of the movement. After each trial the experimenter relocated the cube at its original position.

The experiment consisted of 3 conditions (3 starting positions) that were each presented in a separate block of 25 trials, resulting in 75 trials. The order of the blocks of trials was counterbalanced between subjects.

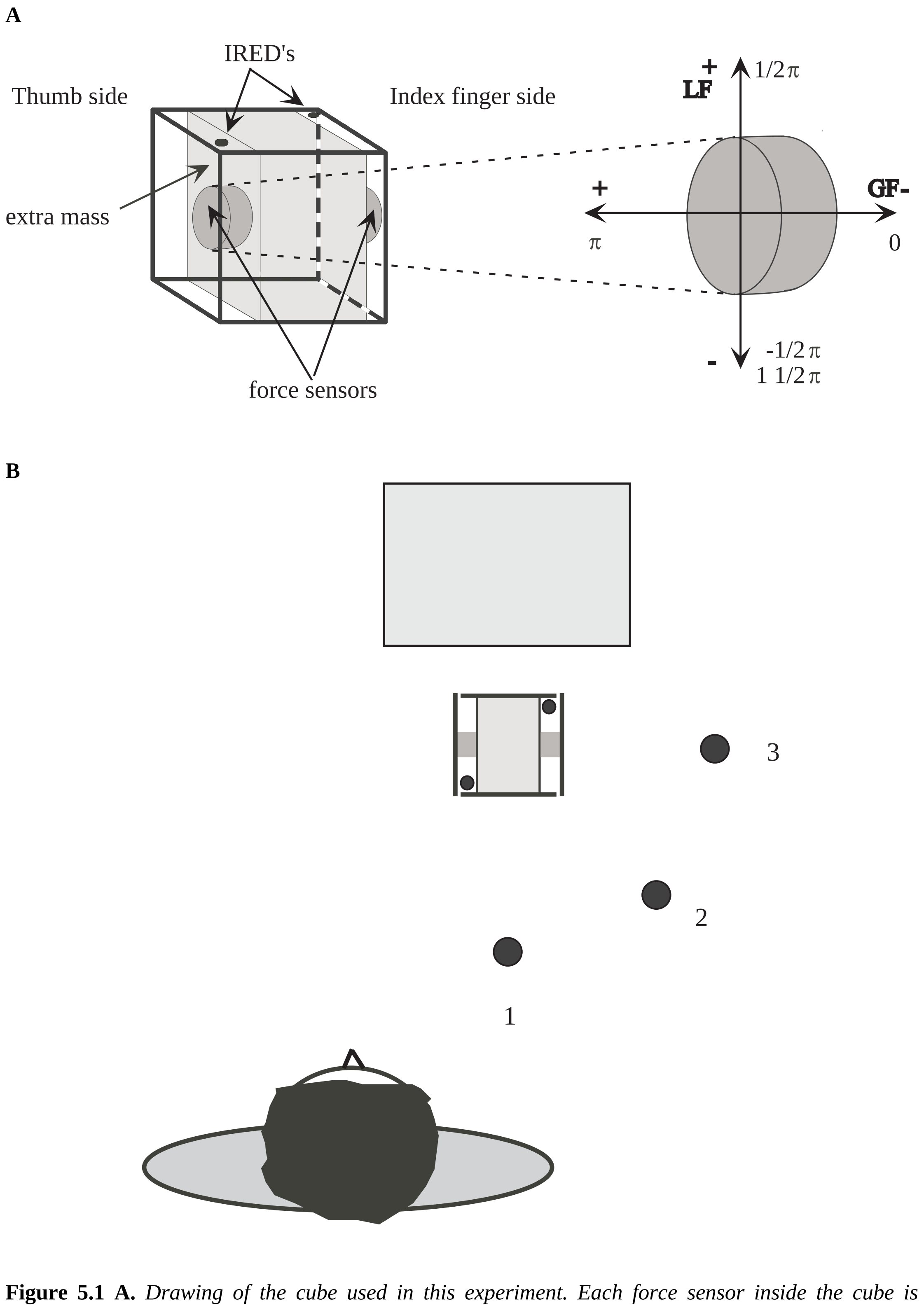

Figure 5.1 A. *Drawing of the cube used in this experiment. Each force sensor inside the cube is attached both to a grasp surface (not shown) and to the extra mass inside the cube. Two IRED's were attached to the top of the cube to measure the position of the cube.* **B.** *Top view of the set-up of the experiment. The black dots indicate the three different starting positions. The cube is shown at its initial position. The plateau onto which subjects had to place the cube is indicated by a grey square. Drawing not to scale.*

Data analysis

Instantaneous velocity and acceleration were computed from position samples of the IRED's. To do so we fit a second order polynomial to 7 position samples (12 ms window) around each position. Based on the three parameters of the fit polynomial we can estimate the finger's position, velocity and acceleration at that instant. This is a convenient method for combining data smoothing and differentiation in a single procedure (Biegstraaten et al. 2003*b;* Smeets et al. 2002). The beginning and end of a digit’s movement to the cube were both based on the tangential velocity of the markers on that digit. The moment of lift-off was based on the upward velocity component of one of the IRED’s of the cube. The onset of the movement of each digit and the moment of lift-off were defined as the last frame before peak velocity in which the velocity was smaller than that on the preceding frame. The offset was defined as the first frame after peak velocity in which the velocity was smaller than that on the following frame (Biegstraaten et al. 2003*b*). The total movement time (MT) was calculated as the time between the onset and offset of the movement for each digit. This total MT was divided into the time from movement onset until initial contact with the cube (MT before contact) and the time from initial contact until movement offset (MT after contact). The period between movement offset and lift-off is referred to as late contact.

The horizontal forces perpendicular to the surface (grip force), the vertical forces applied to the cube (lift force) and the torques in all directions were analysed. The definition of the coordinate system is given in figure 5.1A. In this article we only consider the movements and forces in the grip direction and the lift direction. The moment of initial contact of a digit with the cube was determined on the basis of the grip force. It was defined as the first frame in which the grip force was more than 2 times the standard deviation of the noise and remained above that value until maximum force. We calculated the points of force application for each digit and each sample using the relation between the measured forces and torques. The direction of the applied force was determined at each instant from the lift force and the grip force (for a definition see figure 5.1A). Similarly, we calculated the direction of the velocity of each digit around initial contact with the cube.

For each variable the median value for each subject and condition was used for further statistical analysis. A repeated measures ANOVA was used to evaluate whether there were consistent differences between the starting positions and the digits (across subjects). This was done for the MT, total contact time, time between initial contact and movement offset and for the grip force and lift force at lift-off. To analyze the difference in timing between the digits we determined the difference in initial contact time, and applied a repeated measures ANOVA to evaluate the effects of starting position. Reported standard errors are between subjects.

Results

Figure 5.2 shows example traces of one trial of one subject. Figure 5.2A shows the grip force and the lift force of index finger and thumb and figure 5.2B shows the direction of these applied forces. In this trial the index finger contacts the surface before the thumb does (figure 5.2A). Grip force and lift force are unequally distributed over the digits, which means that the object will not only move vertically. The direction of force changes gradually from the moment of initial contact until it reaches the value that is maintained after lift-off (figure 5.2B).

Figure 5.2C shows the velocity in the grip direction and in the lift direction for each digit. Figure 5.2D shows the direction of these velocities. After the surface is first contacted (time=0) there is still a considerable amount of movement of both the digits (figure 5.2C). The thumb even has a peak in velocity just after contact, illustrating the fact that the movement cannot be considered to have ended at contact. However, although the initial direction of force is a nice continuation of the direction of motion just before contact, the force generated by the contact itself is very modest. The most rapid increase in force occurs after motion offset (figure 5.2A). There are also considerable intentional or accidental shifts and rotations of the digits while in contact with the object. The direction of motion of the digits changes much more than the direction of force (figure 5.2D). One reason for this could be that part of the perpendicular force is transformed into compression of the skin. However, the index finger and thumb did not even stand totally still at the moment of movement offset (figure 5.2C).

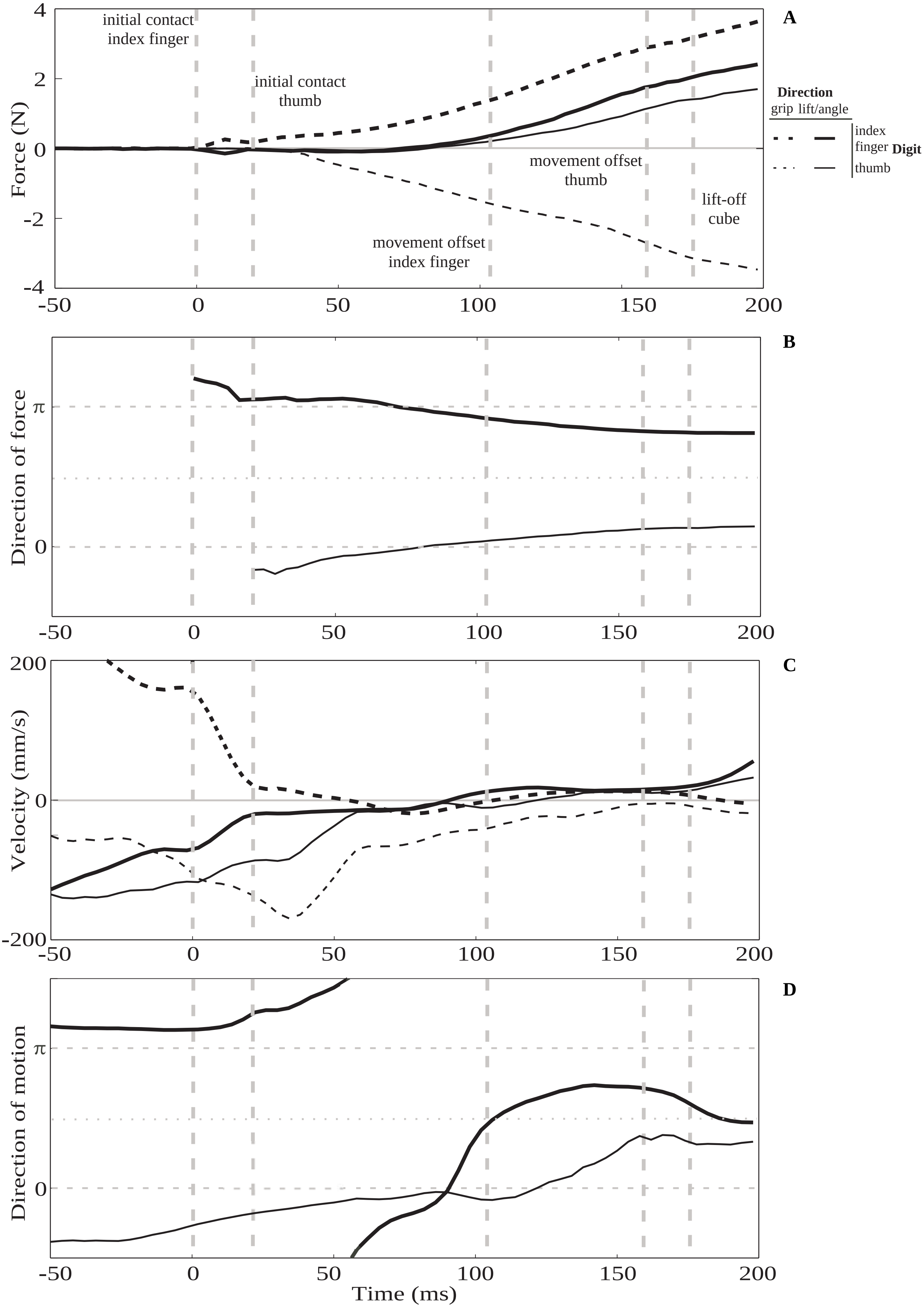
A
B
C
D
initial contact index finger
initial contact thumb
movement offset thumb
lift-off cube
movement offset index finger
Direction
grip lift/angle
index finger
thumb
Digit
Force (N)
Direction of force
Velocity (mm/s)
Direction of motion
Time (ms)
4
2
0
-2
-4
π
200
-200
-50
50
100
150

Figure 5.2 *A single trial of one subject. Thick lines indicate traces of the index finger; thin lines indicate traces of the thumb. If there are two curves for a digit, dashed lines indicate the grip component and solid lines indicate the lift component. Vertical dashed lines indicate the timing of initial contact and movement offset (for each digit) and the moment of lift-off (of the cube). Horizontal dashed lines indicate pure grip force and dotted lines pure lift force. Time zero is the moment of initial contact with the surface.* **A.** *Grip force and lift force for each digit.* **B.** *The direction of the applied force.* **C.** *The two components of each digit's velocity.* **D.** *The direction of the velocity.*

Timing

Figure 5.3 shows the percentage of all trials that reached a certain event at a certain time relative to lift-off (A) or relative to the end of the reaching movement of the index finger and thumb (B, C). For instance, at about 100 ms before lift-off, both digits had contacted the cube in 80 % of the trials. The index finger had stopped moving in 25% of the trials and the thumb in about 8% (see dashed lines in figure 5.3A). The figures look more or less the same for all three starting positions (compare upper, middle and bottom panels). In almost all trials both digits did stop moving (according to our criterion) before the cube was lifted from the table, with the movement offset of the index finger being earlier than the movement offset of the thumb. The time between initial contact and lift-off is more variable (shallower slope) than the time between initial contact and the end of the movement of one of the digits, which validates our criterion for obtaining the latter measure.

Figure 5.4 shows the distribution of the time between movement onset and lift-off int the MT before contact, the MT after contact and late contact. Values are the average across subjects for each digit in each condition. The MT before contact was significantly larger for the thumb (672 ±20 ms) than for the index finger (631 ± 23 ms; $p<0.05$). The average MT after contact was also larger for the thumb (151±14 ms) than for the index finger (138±13ms), but this difference was not significant. The total MT was significantly larger ($p<0.001$) for the thumb (823 ms) than for the index finger (769 ms). The thumb spent less time in late contact (36.4 ± 3.7 ms) than the index finger (64.1 ± 4.5 ms; $p<0.01$). The bars in figure 5.4 are synchronised at the moment of lift-off, which is the same for both digits. The differences in bar lengths therefore indicate the differences in movement onset between the digits. The thumb seems to start moving earlier than the index finger, but this difference is not significant (9.0 ± 4.1 ms; $p=0.9$).

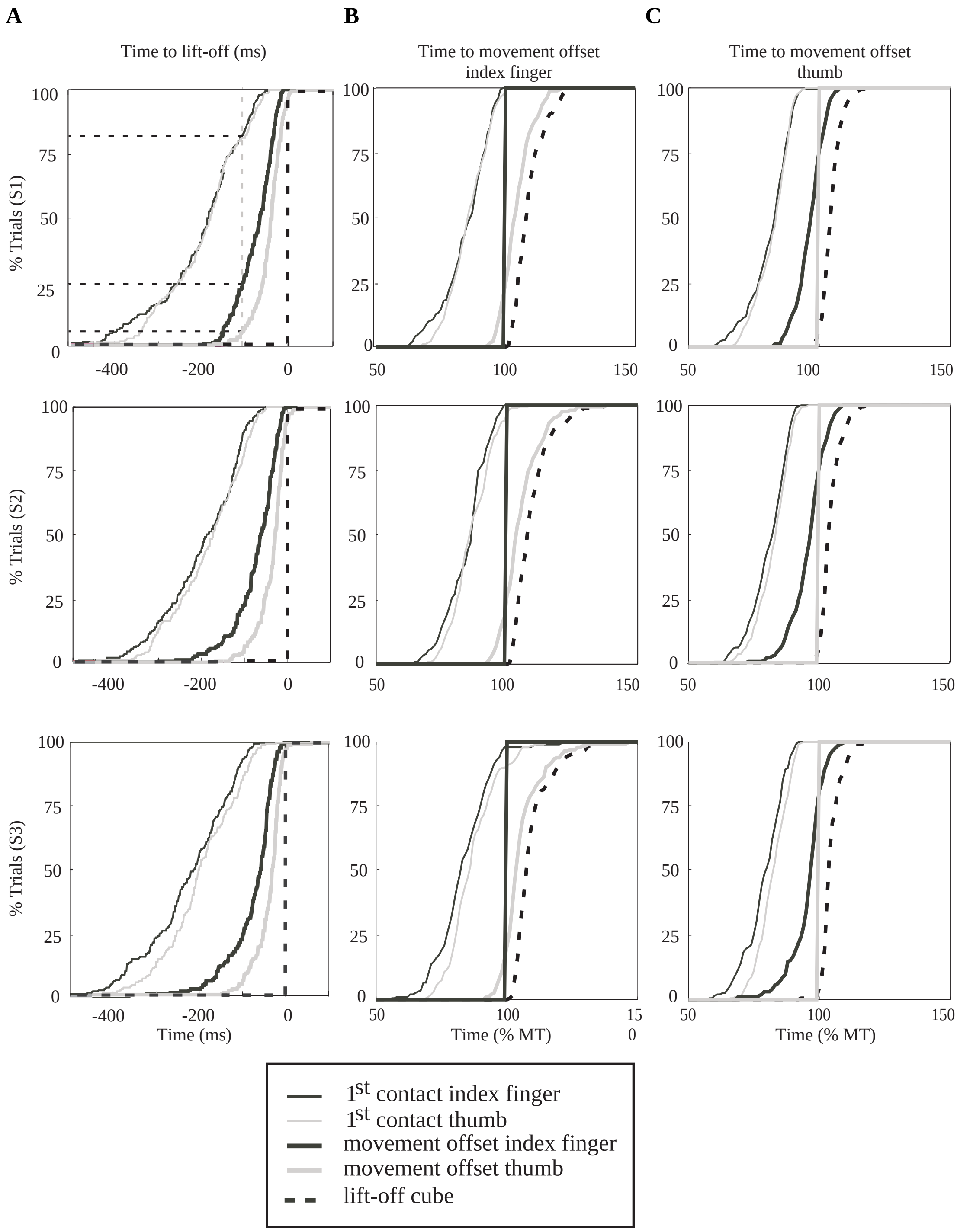

Figure 5.3. *The distribution of the timing of events over trials. Percentage of all trials in which an event has occurred as a function of the time to lift-off in ms (***A***) or of the time to movement offset of the index finger (***B***) or thumb (***C***) as a percentage of the total movement time. Top, middle and bottom row represent starting positions 1, 2 and 3, respectively. Each curve denotes a certain event, as described in the legend. For example, the dashed lines indicate that at about 100 ms before lift-off, both digits had contacted the cube in 80 % of all trials and the index finger had stopped moving in only 25% of the trials and the thumb in about 8%.*

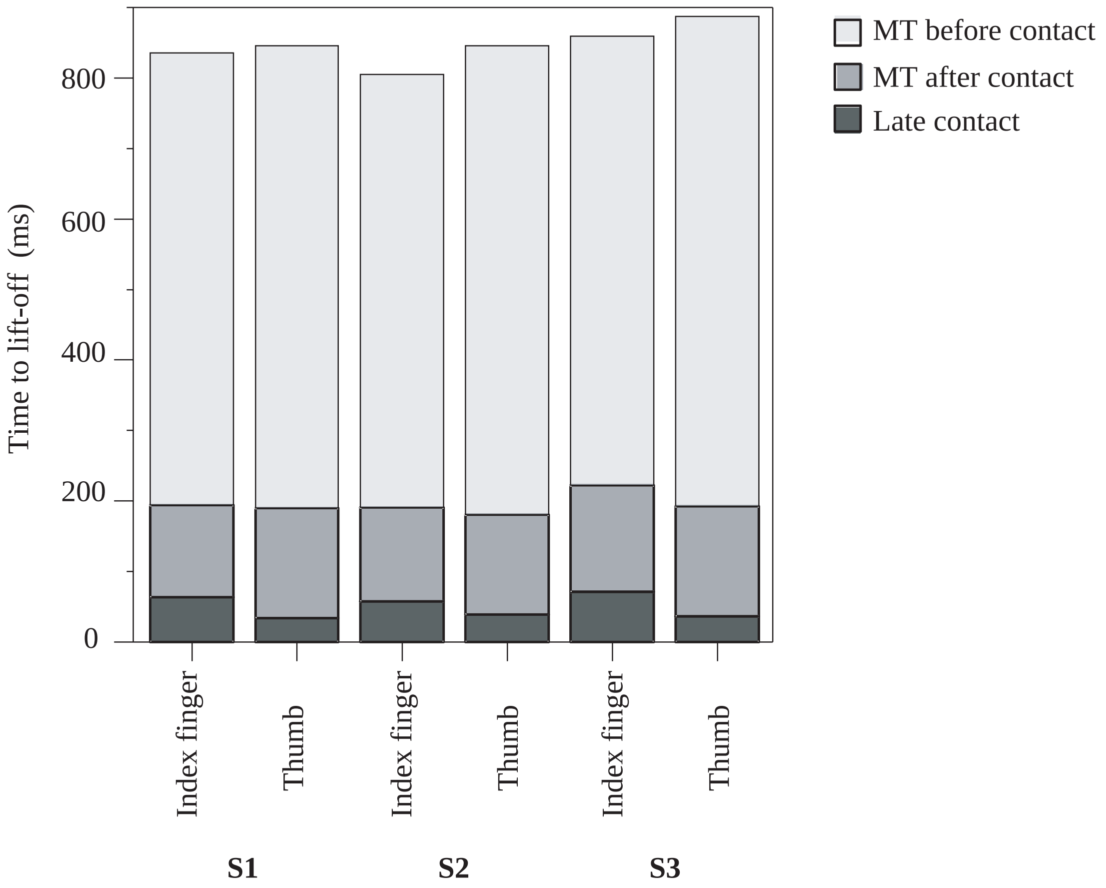

Figure 5.4 *Average timing of movement events. Bar lengths indicate the average time from movement onset until lift-off, for each digit and condition. Each section of a bar denotes a certain time period, as indicated.*

There were no significant differences between starting positions for any of the timing variables, except for the difference between the digits in the moment of initial contact ($p<0.01$). This difference is 5.2 (± 10.1) ms when starting from position 1, 16.8 (± 10.6) ms when starting from position 2 and 37.4 (± 9.1) ms when starting from position 3, with the index finger always contacting the surface first. These asymmetries corresponds with the asymmetries in moement distance (see figure 5.1A).

Force

As in the example in figure 5.2, the average grip force exerted by the index finger at the moment of lift-off was higher (6.40 ±0.40 N) than that exerted by the thumb (5.76 ±0.33 N; $p<0.001$; figure 5.5A). The total lift force at the moment of lift-off was 3.70

± 0.05 N, which was larger than the mass of the cube (3.5 N), as it should be to be able to lift the cube. The lift force produced by the index finger was significantly larger (2.25 ± 0.05 N) than the lift force produced by the thumb (1.45± 0.04N, $p<0.0001$;figure 5.5B). This means that the cube must have tilted a bit after leaving the surface of the table. There were no significant differences between conditions for any of the force variables.

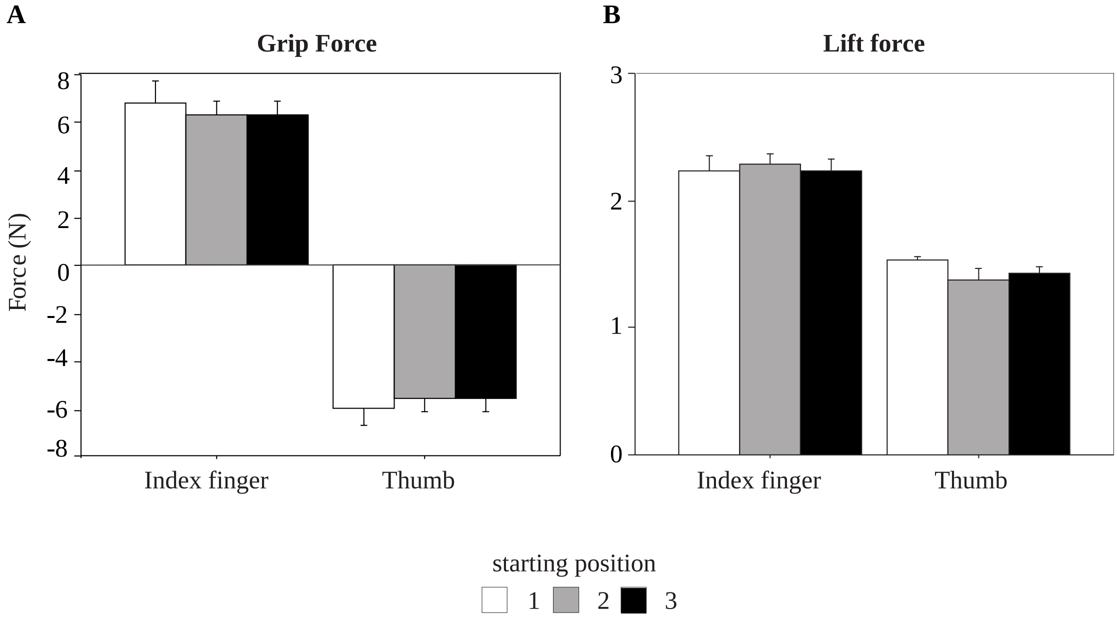

Figure 5.5 *Average grip force (***A***) and lift force (***B***) at lift-off for the index finger and the thumb. White bars represent movements from starting position 1, shaded bars represent movements from starting position 2 and filled bars represent movements from starting position 3.*

Velocity

As already shown in figure 5.2C for a single trial, on average the digits did not totally stand still at movement offset. This is possible because the movement offset was defined by a local minimum in the tangential velocity. The average velocity of the index finger at movement offset was –4.6 (±1.7) mm/s in the lift direction and 14.2 (±2.5) mm/s in the grip direction. For the thumb the velocities were respectively -10.2 (±2.4) mm/s and –42.8 (±4.2) mm/s. Only the velocity (absolute value) in the grip direction differed significantly between the digits ($p<0.001$). All values were significantly different from zero and none differed between starting positions.

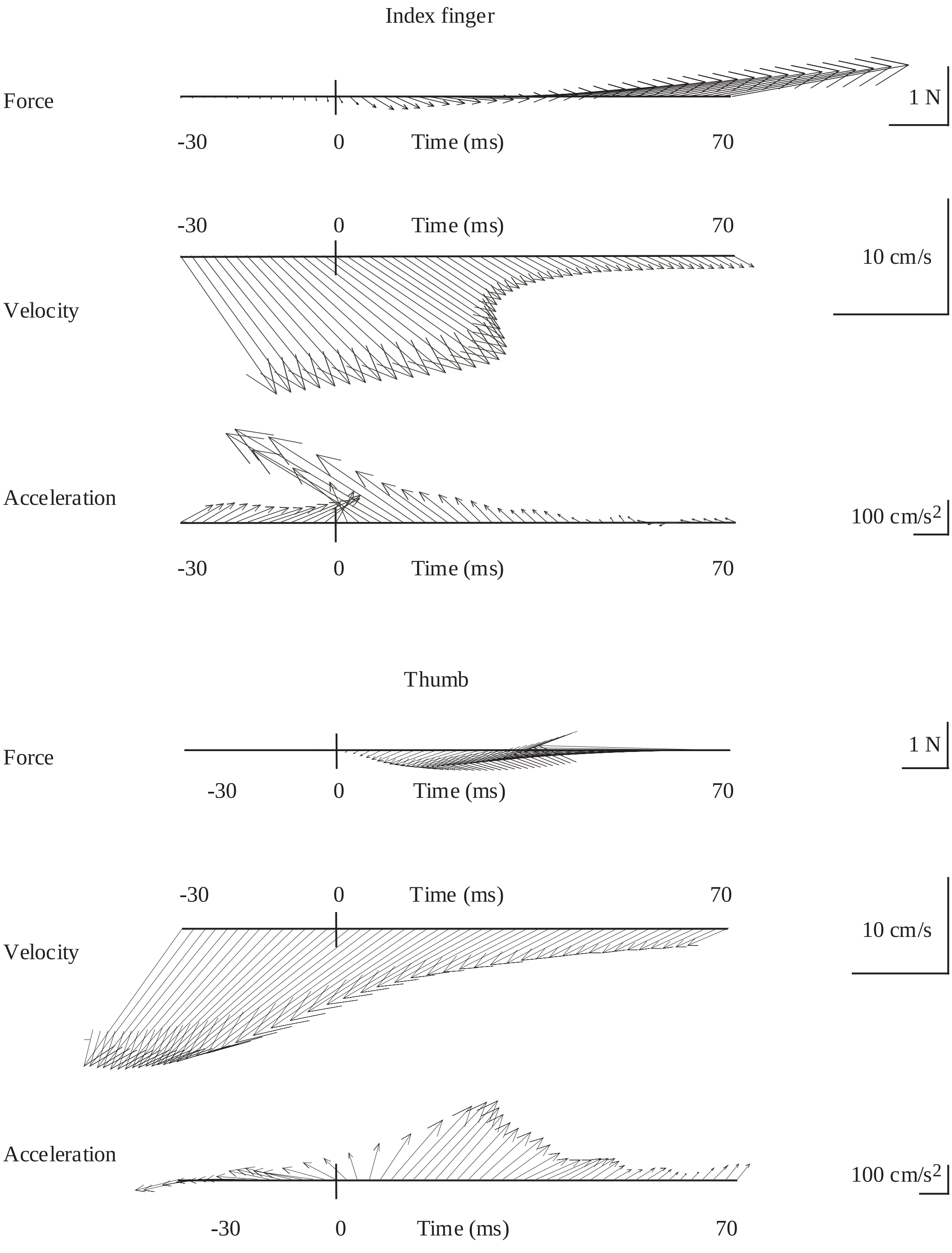

Figure 5.6 *The development of average force and velocity around initial contact. Vector plots for the average direction and amplitude of the applied force, the velocity and the acceleration. Data are presented both for the index finger and for the thumb. Data are averaged over subjects and synchronized at initial contact. Only those trials were averaged in which the time between initial contact and movement offset was more than 70 ms. The data is for starting position 1. The origins of the arrows indicate the time relative to initial contact in steps of 2 ms. Drawing is to scale.*

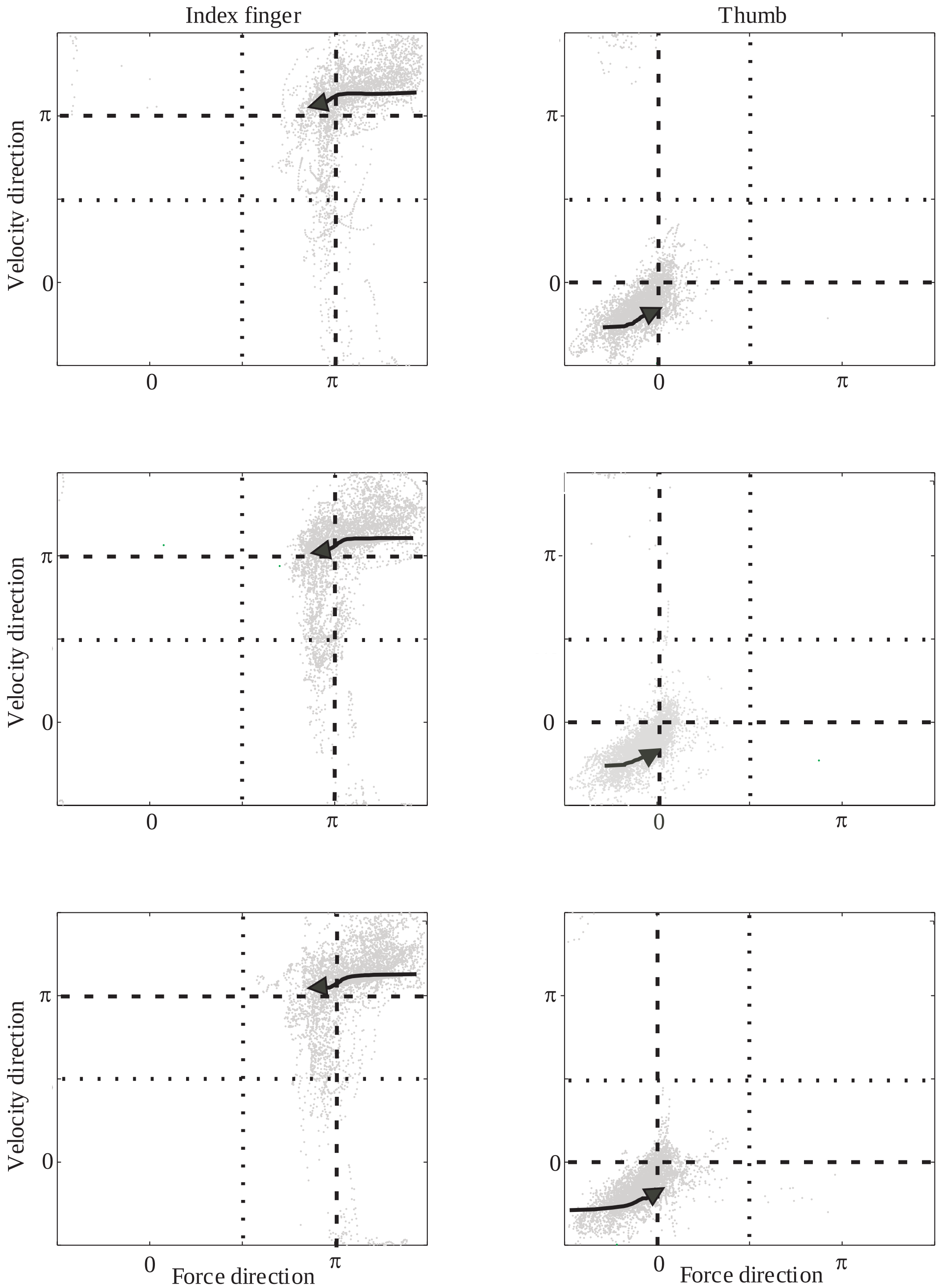

Figure 5.7 *Relation between the direction of the force (horizontal axis) and the direction of the velocity (vertical axis) from the moment of initial contact until 70 ms after initial contact. Each dot represents an instant of a single trial. The arrow indicates the change in direction of the vector average shown in figure 5.6. For all subjects only those trials are shown in which the time between initial contact and movement offset was more than 70 ms. Top, middle and bottom row represent data for starting positions 1, 2 and 3, respectively. Dashed lines indicate a horizontal approach (horizontal line) and a pure grip force (vertical line). Dotted lines indicate an upward motion (horizontal line) and a pure lift force (vertical line).*

Direction of force and velocity

Figure 5.6 shows the vector averages across trials, subjects and conditions for the applied force, velocity and acceleration. Averages are shown for each 2ms from 30 ms before contact until 70 ms after contact (thus synchronised at the initial contact of each digit). Only trials in which the time between initial contact and the movement offset of that digit was more than 70 ms (454 trials for the index finger; 544 trials for the thumb; out of a total of 675 trials) were included. At initial contact, the acceleration clearly changes amplitude and direction. The force is initially directed in the same direction as the digit's motion. The acceleration is directed against the direction of motion of the digit, leading to a reduction of speed without a major change in movement direction. Just after initial contact the applied force is small. This force gradually changes direction (upwards) as it becomes larger. The change in the direction of the force during the first 70 ms after contact is not reflected in a change in direction of velocity or acceleration.

Figure 5.7 shows the relationship between the direction of the force applied by each digit and the direction of its velocity. This is shown for each trial from initial contact until 70 ms after contact (35 data points per trial). The directions of the average force and velocity (as depicted in figure 5.6; i.e. not the average of the directions on individual trials) are represented by the arrows. The applied force at contact is directed a bit downwards for both index finger and thumb (above an angle of π and below 0 for index finger and thumb, respectively; figure 5.7). After contact, as the applied force gradually increases, it also shifts to being perpendicular to the surface (towards π and 0), while the digits keep moving slightly downwards.

Figure 5.8 shows similar average vectors to those in figure 5.6 for the same trials, but for the period from 70 ms before until 30 ms after movement offset. In this figure the values for each digit are synchronised at movement offset rather than at the moment of initial contact. The same data points contribute to figure 5.6 and 5.8 for fast trials but not for slow trials. When averaged in this manner, the direction of the force hardly changes as its amplitude gradually becomes larger. In particular, there is no evident change at movement offset. The direction of the velocity and of the acceleration does change as the reaching movement gradually becomes a lifting movement.

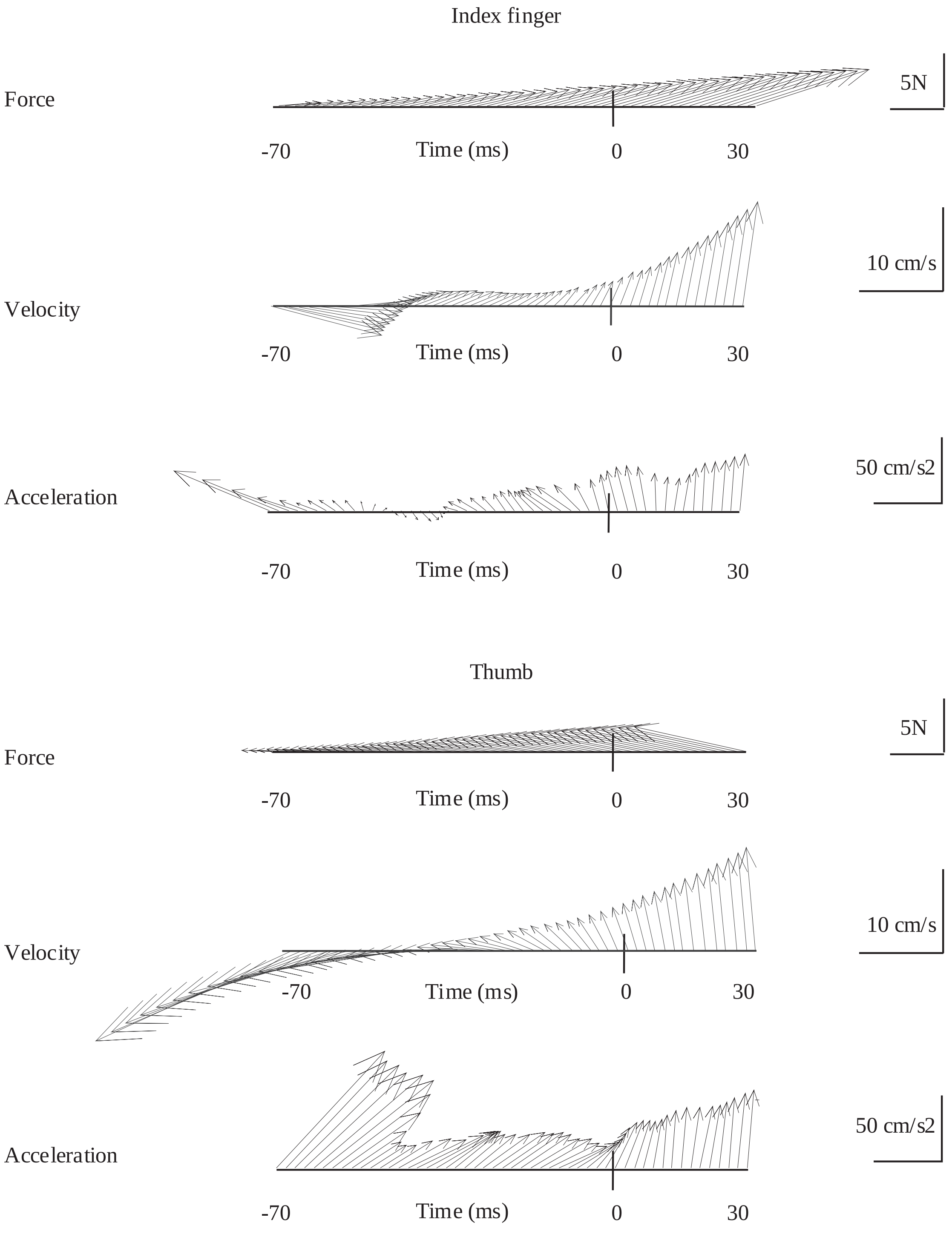

Figure 5.8 *The development of average force and velocity around movement offset. Vector plots for the average direction and amplitude of the applied force, the velocity and the acceleration. Data synchronized at movement offset, and the arrows indicate the time relative to movement offset. All other details as in figure 5.6.*

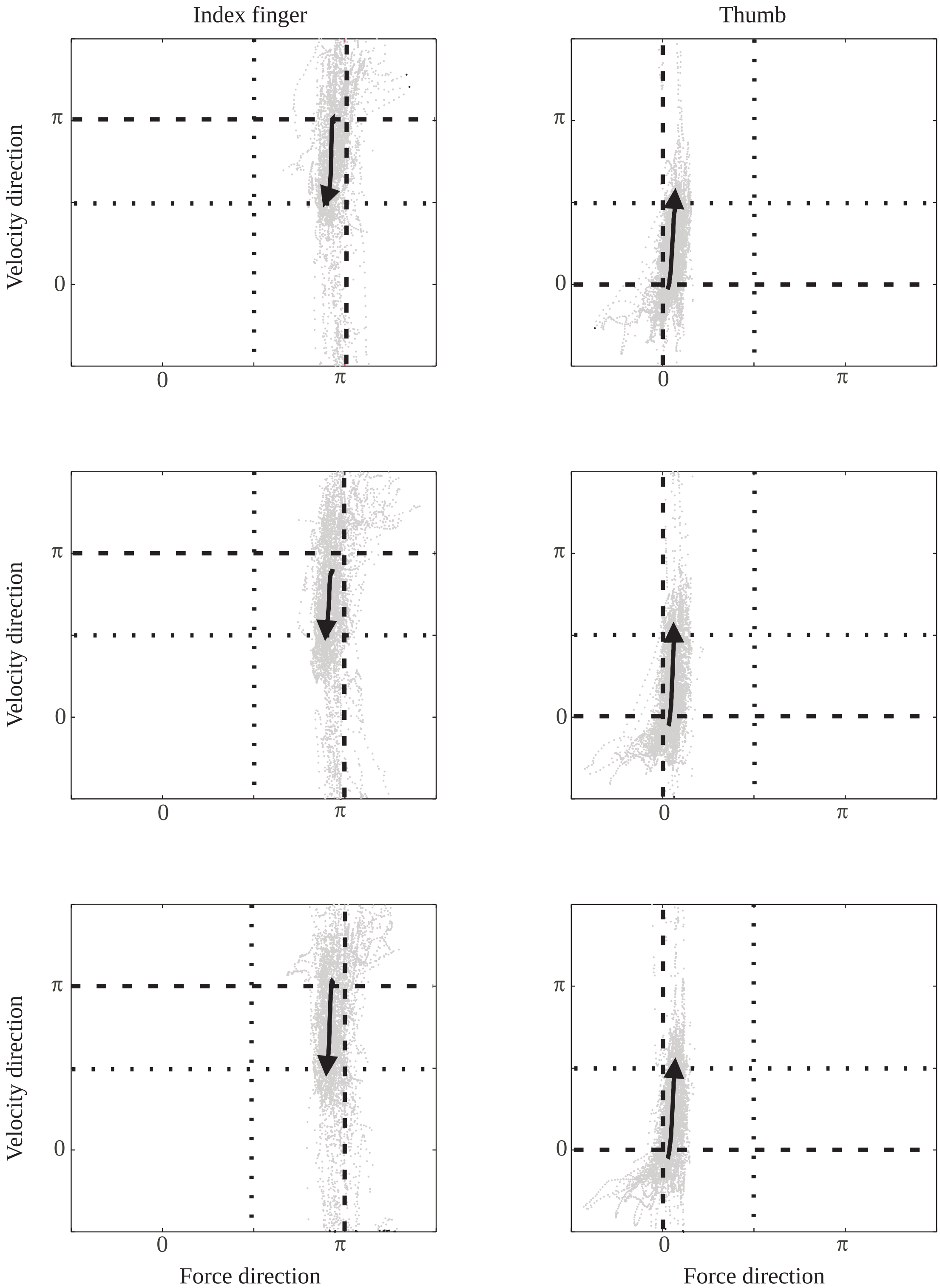

Figure 5.9 *Relation between the direction of the force (horizontal axis) and the direction of the velocity (vertical axis) from 70 ms before movement offset until 30 ms after movement offset. The arrow indicates the change in direction of the vector averages shown in figure 5.8. Other details as in figure 5.7.*

Figure 5.9 shows the relationship between the direction of the applied force and the direction of the velocity during the same period as in figure 5.8. The direction of the velocity changes from perpendicular (0 and π) to upwards (0.5 π) as it should do to lift the cube. The direction of the force is mainly directed perpendicular to the surface of the cube (0 and π). The individual trials (dots) show roughly the same behaviour as the average (arrows).

We have seen that the digits (i.e. the IREDs) move considerably during contact. As the digits (i.e. the IREDs) first move downward and subsequently upward (see figure 5.2C), the net displacement between initial contact and lift-off is rather small (on average -1.3 ±0.3 mm; figure 5.10A). For the control of the cube the point of force application is more important than the position of the nail (i.e. the IRED). This point only moves downward, leading to a net vertical displacement of –5.5 ± 0,7 mm (figure 5.10B), much more than that of the IREDs). The net displacement of the points of force application does not differ significantly between digits (figure 5.10 B). However, the net displacement of the IRED on the tip of the index finger is smaller than that of the thumb (figure 5.10 A). Thus the digits do not movie during contact with the surface in exactly the same manner.

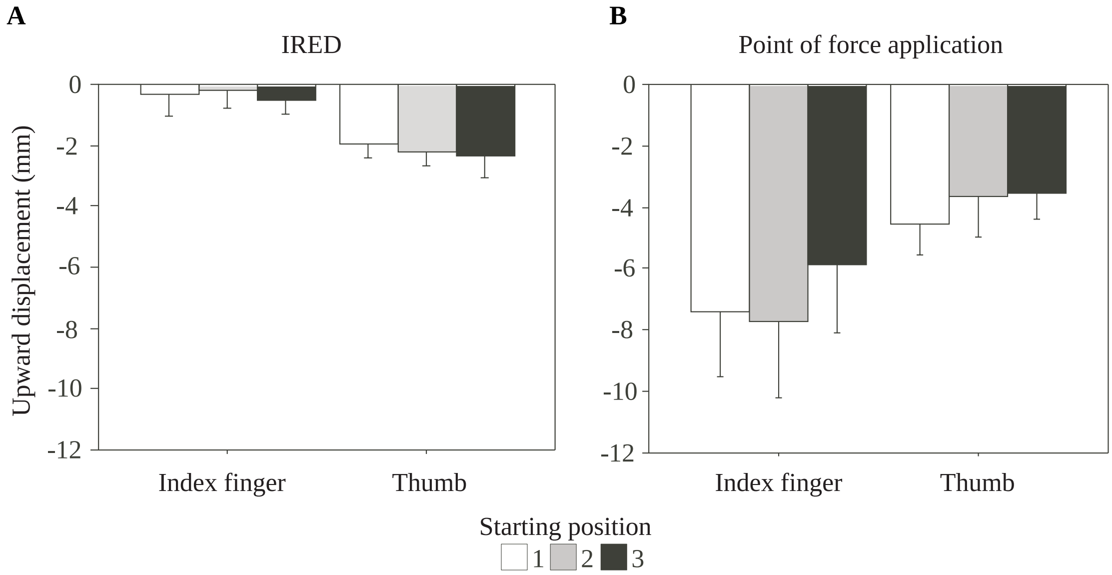

Figure 5.10. *Average vertical displacement of each digit between initial contact and lift-off. Displacement of the IRED's (***A***) and of the points of force application (***B***). White bars represent movements from starting position 1, shaded bars represent movements from starting position 2 and filled bars represent movements from starting position 3.*

Discussion

How does a reaching movement towards an object change into a lifting movement? Smeets & Brenner (2001) showed that the digits move more or less independently towards their designated places of contact on the surface of the target object. The subsequent build-up of forces has also been shown to be controlled separately for each digit (Burstedt et al. 1999; Burstedt et al. 1997; Edin et al. 1992). In the present study we examined whether the final approach and the initial applied forces are somehow related. We let subjects reach for and grasp a cube starting their movement from different positions. We expected to find an effect of the starting position relative to the cube on the movement of each digit. If the movement and force are related, this effect should extend to the way in which the forces build up for lifting. We analysed the movements of the digits and the applied forces and torques during contact with the cube.

In our experiment, the applied forces during the first 20 ms of contact with the cube are small compared to the forces needed to pick the cube off the table. The forces required to lift the cube build up gradually from the moment of initial contact. Nevertheless, the force during the first 20 ms after initial contact is large enough to bring the digit to an almost complete standstill. The high deceleration (see figure 5.6C) and the change in direction of motion during this period, indicates that contacting the surface of the cube helps to stop the movement of both digits. The use of contact force to help stop movements has already been demonstrated for pointing movements towards single and multiple targets (Adam et al. 1997; Biegstraaten et al. 2003*b*). Those experiments showed that although the contact forces help to stop the movement, this is independent of whether another movement will follow. The force at the first target was not larger when subjects could stop at the first target than when they had to move on to a second target, but it was large enough to make the peak velocity occur at 60 % of the movement time (instead of 50%). All these results indicate that the control of the grasping movement is relatively independent of the forces that are exerted on the object to lift it.

The forces just after initial contact are directed slightly downwards (see figure 5.6A), opposite to the direction required to lift the cube. This is no problem since the table supports the cube. The fact that the force is initially directed downwards suggests that the initial contact is part of the reach-to-grasp movement, but not of the lifting movement, because a downward force helps to stop the digit, but does not help to lift the object.

The time between initial contact with the cube and the start of the lifting movement is rather large. Since both the force and the velocity of the digits gradually change during that time, we can conclude that after contact the reaching movement gradually turns into a lifting movement. The first phase of contact with the object is presumably used for gathering tactile information (Johansson and Westling 1984, Westling and Johansson 1984). The long and variable time in contact suggests that reaching and lifting are not part of the same plan, but that the time to start the lifting movement depends on how the reach to grasp was executed.

The fact that an apparently fragile object is approached with more care than an apparently robust object (Marteniuk et al. 1987; Savelsbergh et al. 1996), was one of the arguments to hypothesize a tight coupling between the reaching and lifting phase. As we showed that the forces at contact are not optimized for the lifting movement, there must be another explanation for the careful approach of fragile objects. Probably, the fragility leads to the selection of different grasping points on the surface of the object or it makes people move more accurately to these positions.

We see systematic differences in timing between the thumb and the index finger. These differences are probably related to the starting position of the reaching movement. Movements started earlier and ended later if the digit had to move a longer distance (compare starting position 1 to 3; figure 5.4). The same was found by Boessenkool et al. (1999) in simultaneous bimanual pointing movements to a single target. The present study thus supports the assumption in the model of Smeets and Brenner that the movements of the index finger and the thumb are controlled as independent movements of the digits.

Despite the smooth change in force (figures 5.6 and 5.8), we see a clear change in the relationship between the velocity and the force during the movement (compare figures 5.7 and 5.9). Together with the fact that the digits are moving downwards when they initially contact the object, which is advantageous for grasping but not for lifting, this suggests that the two components (grasping and lifting) are controlled separately. The transition between them is gradual, but it appears that the grasping movement is optimized for achieving a stable grip posture before the lifting movement really starts.

Chapter 6

Summary and Conclusions

We grasp and lift objects many times a day. Most of us perform such a task without any difficulty. However even just grasping the packet of chocolate flakes at the breakfast table is in fact a complex task. Our brain has to – among others - coordinate and select multiple muscles, select the appropriate grasping points and guide the movement in such a way that any unwanted obstacles are avoided.

As soon as our arm, hand or fingers do not function properly, it becomes clear that grasping an object is not so simple. Fundamental research on how the human body performs these daily tasks may therefore be important for designing effective diagnostic procedures and rehabilitation therapies. Knowledge on how grasping behaviour is controlled may for instance be useful for designing and optimizing prosthetic arms or hands. Next to the esthetical value of a prosthetic arm, nowadays prosthetic arms are designed to be capable of grasping and manipulating objects in a close to natural manner. To be able to design such prostheses, the knowledge of how humans naturally use their hands is useful. Therefore defining the requirements of a grasping task (difficulty of the movement, selecting the appropriate grasping points) could be helpful.

Knowledge of grasping behaviour is not only useful for prosthetics. The reverse is also true. Prosthetic hand design gives us an opportunity for understanding prehension better. Grasping behaviour can be modelled and tested directly on the mechanical hand, showing the results of intervention immediately.

In this thesis, we explored what and how healthy humans control when reaching with the hand and grasping with the fingers. We did so by using the model of Smeets and Brenner (1999). At the same time, we investigated the fundamentals of this view. In the following, the chapters 2 to 5 are summarized.

Avoiding the peanut butter and cheese

Chapter 2: The influence of obstacles on the speed of grasping

How do the peanut butter and the cheese beside the packet of chocolate flakes at the breakfast table affect the grasping movement towards that packet? Generally, when an obstacle is placed close to the object to be grasped (target object), the reaching movement slows down. How much slower the movement time is depends on the gap between the target object and the obstacle (Tresilian 1998). Mon-Williams and

Macintosh (2000) tried to discriminate between the classical view on the control of grasping behaviour and the alternative view of Smeets and Brenner. They let subjects grasp a cube that was flanked by obstacles at each side. They only varied the position of the obstacle at the side of the index finger. Mon-Williams and Macintosh analysed the movement times in terms of Fitts' law. Fitts' law describes the relationship between the difficulty of a (pointing) movement and the movement time. The difficulty is determined by the ratio between the distance to the target and the width of the target (index of difficulty; ID).

Mon-Williams and Macintosh defined a separate ID for each view on grasping behaviour. They based the ID for the classical view on the total gap between the obstacles (*Grip ID*). For the alternative view they calculated a separate ID for each finger, based on the gap between the obstacle at the side of that finger and the cube. The ID's for the index finger and for the thumb were then averaged (*Average ID*). The movement times in their experiment could best be described by the Grip ID.

In our opinion, the experiment and analysis of Mon-Williams and Macintosh (2000) were not appropriately set-up to allow a test of the view of Smeets and Brenner. Fitts' law is shown to hold for movements in which the reaching distance to the target and the width of the target are in the *same direction*. However, when grasping a cube with an obstacle at each side, the difficulty of the movement (the gap between the obstacles) is *perpendicular* to the reaching distance. Moreover, altering the positions of obstacles is related to the *grip component* in the classical view of Jeannerod (Jeannerod 1981; 1984). Since according to that view the grip component and the transport component of a grasping movement are controlled independently, the movement time (*transport component*) should not be affected by any change in position of the obstacles (*grip component*).

When reanalysing the data of Mon-Williams and Macintosh (2000), we found that the relationship between the movement time and both ID's still depended on the reaching distance. However, Fitts' law was used to get rid of such dependency. To our opinion it was better to use another model to analyse the movement time, in which the reaching distance and the difficulty of the movement were independent factors (Welford et al. 1969).

In chapter 2, we performed an experiment similar to that of Mon-Williams and Macintosh (2000) and added some refinements. We varied the positions of both obstacles and furthermore we indicated the grasp positions on the cube. In this way, we forced the subjects to grasp symmetrically, making the movement equally difficult for index finger and thumb.

The results showed that the movements became slower when either obstacle was placed closer to the cube. It did not matter whether the closest obstacle was at the side of the index finger or at the side of the thumb. The most difficult condition mainly determined the movement time. This is consistent with Smeets and Brenner's view on the control of grasping behaviour, in which they state that the index finger and the thumb are more or less independently controlled.

The results of this chapter thus indicate that the independent movements of index finger and thumb also can adequately describe grasping behaviour.

Chapter 3: Grasping the Müller-Lyer illusion: More than just a change in length

In chapter 2 we saw that physical obstacles (such as the peanut butter and cheese) placed next to the target object slow down the grasping movement. Whether the closest obstacle to the target object was placed at the side of the index finger or at the side of the thumb did not matter. Not only physical obstacles can influence the grasping movement. In addition, pictorial illusions may influence grasping behaviour. Illusions are known to change the perceived size, length or orientation of an object. However, whether this altered visual information is used to guide the hand movement is still unclear. The illusory surrounding may not only alter the perceived size of an object, parts of the illusion may also be interpreted as being obstacles to the movement. These parts of the illusory surrounding thereby may change the (perceived) *difficulty* of the movement and thereby affect the velocity and the trajectory of the fingers.

In chapter 3 we used the Müller-Lyer figure to test whether this is so. The Müller-Lyer figure consists of a shaft with either inward or outward pointing fins at each end. The outward pointing fins cause the shaft of the figure to look longer than it physically is. In contrast, the inward pointing fins cause the shaft of the Müller-Lyer figure to look shorter than it physically is.

In the experiment, we let subjects grasp a bar that was superimposed onto the shaft of the Müller-Lyer figure. Subject had to start their grasping movement either directly from the bottom of the figure or from the right side of the figure. If only visual size was used to guide the grasping movement, altering the starting position should not have had any effect on the movement. The size information remains the same when starting from the side or from the bottom of the figure. If in contrast the fins of the Müller-Lyer figure are perceived as interfering obstacles then altering the starting position should affect the grasping movement. When starting the movement from the right side of the Müller-Lyer figure, the fins are oriented differently with respect to the trajectory of the fingers than when starting the movement from the bottom of the figure. Therefore, the fins may interfere differently with the trajectories of the index finger and thumb, making the movement more difficult in one situation compared to the other situation.

To discriminate between the use of perceived size and perceived difficulty we analysed the maximum hand opening (Peak Grip Aperture; PGA), timing of the PGA, the movement time and the final grip aperture. We first predicted with the model of Smeets and Brenner (1999) how a change in perceived size and a change in perceived difficulty would affect these variables. For a physically larger object the maximum hand opening is larger. Furthermore, the PGA for a large object is found at 60 % of the movement time instead of 50% of the movement time for a small object (see chapter 3, figure 1). The fingers also open wider when a movement is more difficult. However, the PGA for a more difficult movement is reached *earlier* in time. In other words, more time is spent closing the index finger and thumb to ensure contacting the object at the designated grasping points.

In chapter 3, we found that the PGA was larger for the outward pointing fins, but occurred *earlier* in time. An extra indication that the perceived difficulty was altered is given by the fact that the starting position affected the movement in a similar manner. This matches the simulations for a more difficult or more accurate movement. Even the final grip aperture differed between the inward pointing and outward pointing configurations of the Müller-Lyer figure.

We can conclude from this chapter that a pictorial illusion can influence a grasping movement in more ways than just changing the illusory size. The view of Smeets and Brenner on the control of grasping behaviour can adequately describe such changes.

Independent control of the fingers

Both chapter 2 and 3 indicate that the view of Smeets and Brenner on how grasping movements are controlled can also be used to describe more complex grasping movements involving obstacles. One of the most important features in the view of Smeets and Brenner is that grasping behaviour can be described by the independent movements of the fingers relative to the body instead of relative to each other. In this thesis, we show that the independent movement of the fingers also can adequately describe even the more complex grasping movements.

The notion that the fingers are controlled independently is not new. Several authors found that the grip and load forces are not controlled for the whole grip but for each finger separately (Burstedt et al. 1999; Burstedt et al. 1997; Edin et al. 1992). The relationships found for maximum grip aperture and its timing are merely a consequence of the different requirements for each finger at the end of the movement (Smeets and Brenner 1999). For example: the contact area of the thumb is of course much larger than the contact area of the index finger. Therefore, the required accuracy at contact is different for each finger. In the model of Smeets and Brenner, this can be described by a smaller approach parameter for the thumb leading to a straighter trajectory.

Although of course both fingers are anatomically linked, this does not mean that the grasping behaviour should be modelled accordingly. It has been found that grasping with two fingers of the same hand (unimanual) is remarkably similar to grasping with one finger of each hand (bimanual; Flanagan and Tresilian 1994; Smeets and Brenner 2001). Even in grasps in which the subjects had to push *outwards* instead of *inwards* against the surface to increase the grasp force the grip force develops similar to a "normal" grasp with index finger and thumb (Flanagan and Tresilian 1994).

As already described in chapter 1, we are able to use different strategies that yet are functionally the same. Put in other words, there are different ways to accomplish the same goal. It seems that the coordination of grasping behaviour thus must have a neural basis to act as a functional unit, since the mechanical connections are different for different kinds of grasp formations (Flanagan and Tresilian 1994).

Until now, we have only discussed the control of grasping behaviour when precision grip is used. Most studies involved just two fingers. However, the manipulations we carry out in daily life often involve more than two fingers. Using three or more fingers ensures a more stable grasp. At the same time, it gives more flexibility and possibility during manipulation with the object. Increasing the force applied by one finger, can be compensated for by decreasing the applied force of another finger (Santello and Soechting 2000).

In principle, holding an object with a stable grasp can be achieved with many combinations of fingertip forces, as long as a balance of forces and torques is maintained. Using more fingers has the disadvantage of having to control more degrees of freedom. However, the skeletomotor system decreases the number of degrees of freedom by using more or less fixed coordination patterns between the fingers. Such coordination patterns between multiple fingers are found in several components of grasping behaviour. For instance in the movement of the fingers (Santello et al. 2002; Santello et al. 1998; Soechting and Flanders 1997) in the order of contact of the fingers with the target object (Reilmann et al. 2001a) and in the force applied at the surface of the object (Rearick and Santello 2002; Santello and Soechting 2000)

Although grasping with multiple fingers differs in complexity with a precision grip with only two fingers, it is on the other hand remarkably the same. Subjects adjust the ratio between grip and lift forces to the local friction conditions for each finger (Burstedt et al. 1999). *All* fingers apply forces in such a way that the object does not slip and that excessive forces are avoided. Thus - similar to grasping with just two fingers - the coordination of the grip forces and the lift forces in grasping with three (or more) fingers is also controlled for each finger independently (Burstedt et al. 1999; Flanagan et al. 1999). The time between the fingers that contact the object first and second, is similar for grasping with two or more fingers (Reilmann et al. 2001a). There exists a more or less fixed order in the amount of force applied by each finger, with the index finger applying the highest force (Rearick and Santello 2002).

Next to independent control of each finger, approaching the target object perpendicularly is another important feature of the view of Smeets and Brenner on the control of grasping behaviour. What happens when the fingers first make contact with the surface of the target object is described in chapter 4 and chapter 5.

Making contact with the packet of chocolate flakes

Chapter 4: Impact forces cannot explain the one-target advantage in rapid aimed hand movements

Initial contact with the target object is important in grasping. Since the reaction force to force applied by the fingers to the target object at initial contact (impact force) is directed in the opposite direction, it in principle can stop the finger's movement. Besides this passive mechanism to stop the movement, muscles actively slow down the movement of the hand and fingers.

When the fingers contact the surface of the target object and stop there, the applied force can be very high (as long as it does not hurt too much!). However, if the fingers have to move on to another position there is a problem. In that case, the fingers need to *overcome* the reaction force, and a high impact force is therefore a disadvantage.

Generally pointing movements towards one target are faster when the finger is allowed to stop at that target, than when the finger has to move on to a second target (one-target advantage; see Adam (2000) for an overview). The difference in movement time between two such movements can be up to 15 %. The one-target advantage exists regardless of the size of the targets, the number of targets or the distance to be moved. We hypothesized in chapter 4 that the faster movements to a single target arise because of a larger impact force applied by the finger.

To predict the effects of having a different impact force, we simulated pointing movements using a minimum-jerk model. We defined the end of the simulated movements to the first target as the time the velocity was zero. The difference in impact between the one target condition (finger stops) and the two-target condition (finger moves on) is expressed as a difference in the approach parameter (final deceleration divided by the squared movement time), which indicates how fast the finger moved just before stopping. For the one target condition, the impact (thus the approach parameter) can be as large as one wants. In the two-target condition, the finger must stop and then continue in the same direction so it must decelerate before contact with the first target and accelerate afterwards. Therefore, the approach parameter should be zero at the end of the movement to the first target.

In our simulations, a different impact at the first target led to a slightly larger maximum velocity of the finger that occurred at 60% of the movement time. We compared these predictions to experimental data of an experiment in which subjects had to make similar pointing movements with their index finger. Although the movements to a single target were indeed *faster*, the impact force measured at the first target were *smaller*. The maximum velocity in the one target condition was larger than in the two-target condition. However, both maximum velocities were reached at about 60% of the movement time.

When taking a closer look at the velocity profiles of both target conditions, the final deceleration did seem to differ. However, since the velocity during contact in the two-target condition was rather high, the impact force presumably does not decelerate the finger, but just deforms the skin during contact.

The results of the experiment suggest that a general increase in speed causes the faster movements in the one target condition. Indeed if we simulate this hypothesis with the minimum-jerk model, the maximum velocity in the one target condition is larger but –similar to the two target condition- reached at 50% of the movement time. That in our experiment the maximum velocities in both conditions are reached at 60 % of the movement time indicates that the impact force is used in *both* conditions. However, it is probably not the main factor for stopping the movement of the finger.

Chapter 5: The relation between force and movement when grasping an object with a precision grip.

In chapter 4, we saw that impact with the target in pointing movements is not the main factor for stopping the movement of the finger. However, the impact force is present and may deform the skin during contact. In the view of Smeets and Brenner, a grasping movement is similar to pointing with two fingers. We do not start our grasping movements from the same location when we grasp an object. Besides, the packet of chocolate flakes is not always standing right in front of you at the breakfast table. If the fingers are controlled independently as we saw in the previous chapters, we expect an effect of the starting position relative to the target object on the movement of each finger. In chapter 5, we therefore analysed the movements of the fingers towards the target object, and the forces during until the object was lifted in relation to the preceding reaching movement.

Controlling the ratio between lift forces and grip forces ensures grasp stability. Coordinating these forces prevents the fingers from slipping over the surfaces of the object and at the same time it avoids exerting excessively large forces. The way we grasp an object is important for how we approach an object. If the object seems fragile, one approaches the object with more care than if the object seems very robust (Marteniuk et al. 1987; Savelsbergh et al. 1996). But if the apparently fragile object doesn't turn out to be so, the next time we grasp the same object it will be approached with less care (Savelsbergh et al. 1996). Thus the approaching movement is some how related to the applied force at the object.

In chapter 5, we tested what happens at contact with the target object in relation to the reaching movement before. We let subjects grasp a cube, starting their movement from three different positions, located in a circle from the centre of the cube. Contact forces of the index finger and the thumb were measured. We found that the index finger and the thumb contacted the cube almost at the same time when the starting position was located directly in front of the cube (symmetrical). However, with the more asymmetrical starting locations (making the distance for the thumb larger), the difference between the timing of the initial contact between both fingers became larger. In these conditions, the thumb started to move earlier than the index finger leading to a longer movement time. The time between initial contact of either finger with the surface of the cube and their movement offset was more than 100 ms, which is rather large.

The forces at impact are rather small compared to the grip and lift forces needed to be able to lift the cube, but are large enough to help in slowing down the movement of the fingers. After contact, the amplitude and the direction of both the applied forces and the velocity of the fingers smoothly change. The changes in the direction of the velocity are not reflected by similar changes in the direction of the applied force. Grip and lift force at the moment of lift-off differed between the index finger and thumb, indicating again the independent control of the index finger and the thumb in grasping. Similar to chapter 4, the moment of initial contact does not play a major role when grasping a cube. The movements of the hand and fingers before contact change gradually into the lifting movement of the hand with the cube.

Concluding remarks

From this thesis at least two things become clear. Firstly, we found indications in chapter 2 and 5 that indeed the fingers are controlled independently. In chapter 2, it became clear that when grasping the packet of chocolate flakes that stands between the peanut butter and cheese, the time it takes to complete the movement depends on the smallest gap between one of the obstacles and the packet. It is not important at which side of the packet the obstacle stands. In chapter 5 we saw that also the grip and lift forces are not evenly distributed between the fingers. Therefore, we conclude that grasping behaviour can be described on the basis of the independence of the movements of the fingers. Smeets and Brenner's view on the control of grasping behaviour can even adequately describe more specialized movements such as grasping an object with physical obstacles or illusory obstacles nearby. If their notion on the tendency to approach the target object perpendicularly is true, should be studied in more detail in the future.

Secondly, we found that the moment of contact of the fingers with the surface of the packet of chocolate flakes is not so important. In chapter 4, we saw that in pointing movements, the force at impact does play a role, but it is not the major factor in stopping the finger's movement. In chapter 5 we saw more or less the same for grasping movements. Forces during contact may help in slowing down the fingers' movements, however the control of the reaching movement towards the packet of chocolate flakes is relatively independent from the forces applied at the surface of the packet. Therefore, the applied forces during contact do not play a major role in stopping the movement of the fingers. However, it still could be that the forces during the early phase of contact are predictive for what the subject is intended to do with the object after lift-off. Therefore, instead of studying the relation between the approaching movement and the forces at contact, the contact forces should be studied in relation to the task afterwards. Put in other words, does the applied force when we want to lift the packet of chocolate flakes to spread the flakes at our bread differ from when we want to lift the packet to pass it to our partner at table?

Hoofdstuk 6

Samenvatting en Conclusies

Vele malen op een dag grijpen we een object en tillen het op. Voor de meeste van ons kost dit geen enkele moeite. Maar zelfs het oppakken van de doos chocoladevlokken aan de ontbijttafel is in feite een complexe taak. Onze hersenen moeten - onder andere - meerdere spieren selecteren en coördineren, de juiste posities voor de vingers op het object bepalen en de beweging op zo'n manier sturen dat obstakels kunnen worden ontweken.

Dat grijpen niet zo simpel is, merken we vaak pas op het moment dat een arm, hand of de vingers niet goed functioneren. Fundamenteel onderzoek naar het functioneren van het menselijk lichaam is belangrijk voor het ontwikkelen van effectieve diagnostische methodieken en revalidatie therapieën. Kennis over de aansturing van grijpbewegingen is bijvoorbeeld noodzakelijk voor het ontwerpen en optimaliseren van arm- of handprotheses. Zo'n prothese heeft natuurlijk een grote esthetische waarde. Daarnaast echter, kan men tegenwoordig met deze protheses ook op een uiterst natuurlijke manier naar objecten grijpen en deze manipuleren. Kennis over hoe mensen van nature hun arm en hand gebruiken en aansturen is nodig om deze protheses te kunnen ontwerpen. Het definiëren van taakeisen zoals (de moeilijkheid van de grijpbeweging en de selectie van de juiste contactpunten op het object) kunnen hierbij van nut zijn.

Kennis van grijpbewegingen is dus nuttig voor het onderzoek naar, en het ontwikkelen van protheses. Omgekeerd, geven protheses ons de mogelijkheid om (de aansturing van) grijpbewegingen beter te kunnen begrijpen. Natuurlijke grijpbewegingen kunnen met behulp van een mechanische hand gesimuleerd worden, waardoor het effect van veranderingen in de aansturing direct zichtbaar zijn.

In dit proefschrift hebben we onderzocht *wat* en *hoe* mensen aansturen in wijs- en grijpbewegingen. Hiervoor hebben we gebruik gemaakt van het model van Smeets en Brenner (1999). Daarnaast hebben we ook de basis principes van dit model onderzocht. Hieronder volgt een korte samenvatting van de hoofdstukken 2 tot en met 5. Na de samenvatting volgen enkele conclusies.

Het ontwijken van de kaas en pindakaas

Hoofdstuk 2: De invloed van obstakels op de grijpsnelheid

Hoe beïnvloeden de kaas en de pindakaas uit het beschreven voorbeeld de reik- en grijpbeweging naar de doos met chocoladevlokken? In het algemeen geldt dat de snelheid van de reikbeweging afneemt als er een obstakel in de buurt van het te grijpen object (doelobject) wordt geplaatst. Hoeveel de bewegingstijd toeneemt hangt af van de ruimte tussen het doelobject en het obstakel (Tresilian, 1998).

In hoofdstuk 2 hebben we geanalyseerd wat er gebeurt als er naast het doelobject twee obstakels staan. Dit experiment was qua opzet voor een groot deel gelijk aan het experiment in Mon-Williams and Macintosh (2000). Wij hebben echter de positie van *beide* obstakels gevarieerd en de contactposities op het doelobject aangegeven. Het aangeven van de contactposities dwong de proefpersonen om het object symmetrisch op te pakken. De bewegingen van de wijsvinger en van de duim zijn daardoor even moeilijk.

De bewegingen werden langzamer als één van beide obstakels dichter bij het doelobject was geplaatst. Het was onbelangrijk *welk* obstakel en dichtst bij het doelobject stond. Dit komt overeen met de opvatting van Smeets en Brenner over de aansturing van grijpbewegingen. Zij beweren namelijk dat de wijsvinger en de duim min of meer onafhankelijk worden aangestuurd.

Hoofdstuk 3: Het grijpen van de Müller-Lyer illusie: Meer dan alleen een lengteverandering

In hoofdstuk 2 zagen we al dat fysieke obstakels (zoals de kaas en de pindakaas op de ontbijttafel) direct naast het doelobject, de snelheid van de totale beweging doen afnemen. Maar niet alleen fysieke obstakels kunnen een grijpbeweging beïnvloeden. Ook illusoire getekende figuren kunnen een grijpbeweging beïnvloeden. Het is bekend dat deze illusies de waargenomen grootte, lengte of oriëntatie van een object kunnen veranderen. Het is echter onbekend of deze veranderde waargenomen grootte ook gebruikt wordt om de beweging van de hand te leiden. De illusoire omgeving hoeft niet alleen de waargenomen grootte van een object te veranderen. De verschillende elementen van de getekende illusie zouden ook als obstakels voor de beweging geïnterpreteerd kunnen worden. Daarmee kunnen deze grafische elementen de (waargenomen) moeilijkheid van de beweging veranderen.

In hoofdstuk 3, lieten we de proefpersonen een staafje grijpen dat op een getekende dubbele pijl was geplaatst. Er waren twee verschillende dubbele pijlen. De naar binnen gerichte pijlen laat het staafje langer lijken. De naar buiten gerichte pijlen laten het staafje juist korter lijken dan het echt is. Daarnaast varieerden we de startpositie van de grijpbeweging. De maximale handopening was groter voor de naar binnen gerichte pijlen (staafje lijkt langer), maar deze werd *eerder* in de tijd bereikt. Dit komt overeen met gesimuleerde bewegingen met een hogere moeilijkheidsgraad. De verandering van startpositie beïnvloedt de grijpbeweging op een soortgelijke manier, wat een extra indicatie is dat de waargenomen moeilijkheid verschilt tussen de condities. Uit het feit dat zelfs de handopening bij het oppakken van het staafje verschilde tussen configuraties van de Müller-Lyer figuur, kunnen we opmaken dat de gehele grijpbeweging beïnvloed wordt door de illusie.

Uit dit hoofdstuk kunnen we concluderen dat een getekende illusie een grijpbeweging op andere manieren kan beïnvloeden dan alleen door een verandering van de illusoire grootte. De visie van Smeets en Brenner op de aansturing van grijpbewegingen kan deze veranderingen goed beschrijven.

Onafhankelijke aansturing van de vingers

Zowel hoofdstuk 2 als hoofdstuk 3 geven aan dat de opvatting van Smeets en Brenner over de aansturing van grijpbewegingen ook gebruikt kan worden om complexe grijpbewegingen te beschrijven. Eén van de belangrijkste kenmerken hun opvatting is dat een grijpbeweging beschreven kan worden door de onafhankelijke bewegingen van elke vinger ten opzichte van het lichaam, in plaats van bewegingen ten opzichte van elkaar. Uit dit proefschrift blijkt dat ook de complexere grijpbewegingen op deze manier adequaat beschreven kunnen worden.

Het idee dat de vingers onafhankelijk worden aangestuurd, is niet nieuw. Verschillende auteurs hebben al eerder gevonden dat bijvoorbeeld de knijpkrachten en optilkrachten bij het vasthouden van een object voor elke vinger apart worden aangestuurd (Burstedt et al. 1999; Burstedt et al. 1997; Edin et al. 1992). De gevonden relaties tussen de maximale handopening en de timing ervan, worden vooral veroorzaakt door de verschillende eisen voor elke vinger aan het eind van de beweging (Smeets and Brenner 1999). Het contactoppervlak van de duim is bijvoorbeeld veel groter dan het contactoppervlak van de wijsvinger. Daardoor is de benodigde nauwkeurigheid bij het contact lager voor de duim. In het model van Smeets en Brenner wordt deze nauwkeurigheid beschreven door de "approach parameter (a_p)". Een lagere nauwkeurigheid voor de duim geeft een kleinere a_p , wat in het model leidt tot een meer rechtlijnige beweging van de duim.

Hoewel natuurlijk beide vingers via anatomische structuren aan elkaar verbonden zijn, betekent dit niet dat grijpbewegingen ook als zodanig gemodelleerd moeten worden. Het grijpen met twee vingers van dezelfde hand (uni-manueel), lijkt verrassend veel op het grijpen met één vinger van elke hand (bi-manueel; Flanagan and Tresilian 1994; Smeets and Brenner 2001). Zelfs bij grijpbewegingen waarbij de proefpersonen *naar buiten* tegen het oppervlak van een object moesten duwen in plaats van *naar binnen,* ontwikkelt de knijpkracht zich op een "normale" (Flanagan and Tresilian 1994) manier.

Zoals al beschreven in hoofdstuk 1, zijn we in staat om verschillende strategieën voor aansturing te gebruiken die functioneel tot het zelfde resultaat leiden. Oftewel, er zijn verschillende manieren om een zelfde doel te bereiken. Omdat de mechanische verbindingen verschillend zijn voor verschillende grijpformaties, heeft het als één geheel aansturen van de grijpbewegingen blijkbaar een neurale basis (Flanagan and Tresilian 1994).

Tot nu toe hebben we – zoals in de meeste studies- alleen de aansturing van grijpbewegingen bestudeerd bij het grijpen met vinger en duim. Maar in het dagelijks leven manipuleren we objecten meestal met meer dan twee vingers. Het gebruik van drie of meer vingers geeft een meer stabiele grip. Tegelijkertijd, geeft het gebruik van drie of meer vingers meer flexibiliteit en mogelijkheden tijdens manipulatie van het object. Toename van de geleverde kracht van de ene vinger kan gecompenseerd worden door een afname van de geleverde kracht van een andere vinger (Santello and Soechting 2000).

In principe kan het stabiel vasthouden van een object bereikt worden met veel verschillende combinaties van krachten, zolang als het evenwicht van krachten en momenten maar bewaard wordt. Het gebruik van meerdere vingers heeft als nadeel dat er meer vrijheidsgraden gecontroleerd moeten worden. Het spierskeletsysteem vermindert het aantal vrijheidsgraden door min of meer vaste coördinatie patronen tussen de vingers te gebruiken. Deze coördinatie patronen zijn zichtbaar in de verschillende delen van een grijpbeweging. Bijvoorbeeld in de beweging van de vingers naar het doelobject (Santello et al. 2002; Santello et al. 1998; Soechting and Flanders 1997), in de (vaste) volgorde van contact van de vingers met het doelobject (Reilmann et al. 2001) en in de geleverde kracht op het oppervlak van het doelobject (Rearick and Santello 2002; Santello and Soechting 2000).

Naast de verschillen in complexiteit tussen het grijpen met meerdere vingers en het grijpen met maar twee vingers (precisie grip), zijn er ook veel overeenkomsten. Proefpersonen passen bijvoorbeeld de verhouding tussen knijp- en optilkrachten aan naar de lokale wrijvingseisen voor elke vinger (Burstedt et al. 1999). De krachten van *alle* vingers worden zo geleverd, dat het object niet kan slippen en dat extreem hoge krachten worden vermeden. Overeenkomstig met het grijpen met twee vingers, wordt de coördinatie van knijp en optilkrachten bij het grijpen met gebruik van drie of meer vingers voor elke vinger apart aangestuurd (Burstedt et al. 1999; Flanagan et al. 1999). De tijd tussen de eerste en de tweede vinger die contact maken met het doelobject is gelijk voor het grijpen met twee of net meerdere vingers (Reilmann et al. 2001). Er bestaat een min of meer vaste volgorde in de hoeveelheid kracht die per vinger wordt geleverd,

Naast de onafhankelijke aansturing van elke vinger, is het loodrecht benaderen van het doelobject een belangrijk kenmerk in de opvatting over de aansturing van grijpbewegingen van Smeets en Brenner. In hoofdstuk 4 en hoofdstuk 5 wordt beschreven wat er gebeurt op het moment dat de vingers contact maken met het doelobject.

Contact maken met de doos chocoladevlokken

Hoofdstuk 4: Contactkrachten kunnen het één-doel-voordeel in snelle wijsbewegingen niet verklaren.

Het moment waarop voor het eerst contact wordt gemaakt met het doelobject is belangrijk bij grijpen. De reactiekracht op de kracht uitgeoefend door de vingers op het doelobject (contactkracht) is tegengesteld gericht. In principe kan deze reactie kracht de beweging van de vinger stoppen. Naast dit passieve mechanisme, zorgen spieren voor het actief afnemen van de snelheid van de vingers en de hand.

De uitgeoefende kracht kan en mag erg hoog zijn als de vingers na het maken van contact met het oppervlak van het doelobject, niet verder hoeven te bewegen. Echter, er is een probleem als de vingers moeten door bewegen naar een volgende positie. In dat geval, moeten de vingers de reactiekrachten *overwinnen*. Een hoge contactkracht is daarbij een nadeel.

Wijsbewegingen naar een doel zijn sneller als de vinger mag stoppen op dat doel, dan wanneer de vinger moet door bewegen naar een tweede doel (één-doel-voordeel; zie Adam (2000) voor een overzicht). Het verschil in bewegingstijd tussen twee van deze bewegingen kan oplopen tot ongeveer 15%. In hoofdstuk 4 veronderstellen we dat de snelle beweging naar één enkel doel veroorzaakt wordt door een grote door de vinger uitgeoefende contactkracht. Eerst hebben we de effecten van deze hypothese gesimuleerd en deze voorspellingen hebben we vergeleken met de resultaten van een experiment waarin de proefpersonen gelijksoortige wijsbewegingen met de wijsvinger maakten. Hoewel de bewegingen in het experiment naar één enkel doel inderdaad *sneller* waren, was de gemeten contactkracht *kleiner*. De maximum snelheid in de conditie met maar één doel was weliswaar hoger dan in de conditie met twee doelen, maar in beide gevallen werd de maximum snelheid op ongeveer 60% van de bewegingstijd bereikt.

Als we de snelheidsgrafieken iets nauwkeuriger bestuderen, zien we dat de vertraging op het eind van de beweging naar het eerste doel toch lijken te verschillen tussen de condities. Echter, sinds de snelheid gedurende de contactfase met het eerste doel in de conditie met twee doelen nogal hoog was, wordt de contactkracht waarschijnlijk niet gebruikt om de beweging van de vinger af te remmen. Het is zeer waarschijnlijk dat de contactkracht alleen verschuiving van de huid veroorzaakt. Sinds de maximum snelheid op 60% wordt bereikt, denken wij dat de contactkracht juist gebruikt wordt in *beide* condities, maar dat het waarschijnlijk niet de belangrijkste factor is in het vertragen van de vinger.

Hoofdstuk 5: De relatie tussen kracht en beweging bij het grijpen van een object met wijsvinger en duim.

In hoofdstuk 4 hebben we gezien dat contact maken met het doel bij wijsbewegingen niet de bepalende factor is in het afremmen van de beweging van de vinger, waarschijnlijk veroorzaakt de contactkracht alleen huidverschuivingen. Smeets en Brenner (1999) beschouwen een grijpbeweging als het wijzen met twee vingers. Normaliter beginnen niet alle grijpbewegingen naar een object vanaf dezelfde locatie. Daarnaast staat de doos chocoladevlokken natuurlijk niet altijd precies recht voor je op de ontbijttafel. Als elke vinger onafhankelijk wordt aangestuurd, zoals bleek uit de vorige hoofdstukken, dan verwachten we ook een effect van de startpositie relatief tot het object op de beweging van elke vinger. In hoofdstuk 5 moesten proefpersonen een kubus optillen, beginnend vanaf drie verschillende startposities. De bewegingen en de contactkrachten van de wijsvinger en de duim werden geanalyseerd.

De krachten op het moment van eerste contact zijn vrij klein vergeleken bij de benodigde knijp- en tilkrachten voor het optillen van de kubus. De krachten tijdens de eerste 20 ms na het eerste contact zijn echter groot genoeg om de beweging van de vingers flink te vertragen. In eerste instantie zijn de krachten een beetje naar beneden gericht. Dit is voordelig voor het afremmen, maar niet voor het tillen van het object. Gedurende de nogal lange contactfase veranderen zowel de kracht als de snelheid geleidelijk. De lange en variabele contacttijd geeft aan dat de reikbeweging en de grijpbeweging geen deel uitmaken van eenzelfde plan, maar dat de tilbeweging afhangt van de uitvoering van de reikbeweging.

Net als in hoofdstuk 4, speelt het eerste moment van contact geen grote rol bij het grijpen van de kubus. De bewegingen van de hand en de vingers voor contact met de kubus gaan geleidelijk over in de tilbeweging van de hand met de kubus. Toch verandert de relatie tussen de snelheid en de kracht in deze periode. Dit suggereert dat de het grijpen van het object en het optillen er van, onafhankelijk worden aangestuurd en dat de grijpbeweging geoptimaliseerd is voor het bereiken van een stabiele grip.

.

Conclusies

Uit dit proefschrift worden tenminste twee dingen duidelijk. Als eerste geven hoofdstuk 2 en hoofdstuk 5 aan dat de vingers inderdaad onafhankelijk worden aangestuurd. In hoofdstuk 2 werd het duidelijk dat bij het grijpen van de doos chocolade vlokken midden tussen de pindakaas en kaas, de bewegingstijd afhangt van de kortste afstand tussen de vlokken en één van de obstakels. In hoofdstuk 5 zagen we dat de ook knijp- en optilkrachten niet gelijkelijk verdeeld zijn over beide vingers. Daarom kunnen we concluderen dat grijpbewegingen goed beschreven kunnen worden op basis van de onafhankelijke, individuele bewegingen van de vingers. De opvatting van Smeets en Brenner over de aansturing van grijpbewegingen kan ook de meer gespecialiseerde bewegingen zoals het grijpen van een object met fysieke of illusoire obstakels ernaast goed beschrijven. Hun tweede aanname, dat de vingers het doelobject ongeveer loodrecht benaderen, moet nog verder onderzocht worden.

Ten tweede vonden we dat het contactmoment van de vingers met het oppervlak van het doelobject niet zo heel belangrijk is. In hoofdstuk 4 zagen we dat in wijsbewegingen de contactkracht niet de belangrijkste variabele is in het vertragen van de vinger. In hoofdstuk 5 zagen we ongeveer hetzelfde voor grijpbewegingen. De krachten tijdens de contactfase dragen waarschijnlijk wel bij aan het vertragen van de beweging van de vingers, maar de aansturing van de reikbeweging naar de doos chocoladevlokken is redelijk onafhankelijk van de aansturing van de uitgeoefende krachten op het oppervlak van de doos. De geleverde krachten spelen daarom niet zo'n grote rol in het vertragen van de vingers. Het is nog wel mogelijk dat de krachten tijdens de eerste fase van contact voorspellend zijn voor wat de proefpersoon met het object wil gaan doen na het optillen. Daarom is het interessant om ook de contactkrachten te bestuderen in relatie tot de taak erna. Oftewel, verschilt de geleverde kracht als we de doos chocoladevlokken oppakken om het de vlokken op een boterham te doen van de geleverde kracht als we de doos alleen maar aan onze partner willen doorgeven?

References

Adam, J, Bruggen, Dvd and Bekkering, H (1993). The control of discrete and reciprocal target-aiming responses: Evidence for the exploitation of mechanics. *Human Movement Science,* 12:353-364.

Adam, J, Loon, Ev, Paas, F, Drost, M, Dongen, Mv and Kodde, R (1997). Impact forces of one- and two-element target-aiming responses. *Human Movement Science,* 16: 369-377.

Adam, J, Niewenstein, J, Huys, R, Paas, F, Kingma, H, Willems, P and Werry, M (2000). Control of rapid aimed hand movements: The one-target advantage. *Journal of Experimental Psychology: Human Perception and Performance,* 26:295-312.

Adam, JJ, Helsen, WF, Elliott, D and Buekers, MJ (2001). The one-target advantage in the control of rapid aiming movements: The effect of practice. *Journal of Human Movement Studies,* 41, 301-313.

Andersen, P, Hagan, PJ, Phillips, CG and Powell, TP (1975). Mapping by microstimulation of overlapping projections from area 4 to motor units of the baboon's hand. *Proceedings of the Royal Society of London. Series B. Biological sciences.,* 188, 31-6.

Arbib, MA (1981). Perceptual structures and distributed motor control. Handbook of Physiology. Section 1. V. B. Brooks. Baltimore, Williams et Wilkins. **2: Motor control:** 1449-1480.

Biegstraaten, M, Smeets, JBJ and Brenner, E (2003*a*). The influence of obstacles on the speed of grasping. *Experimental Brain Research,* 149, 530-4.

Biegstraaten, M, Smeets, JBJ and Brenner, E (2003*b*). Impact forces cannot explain the one-target advantage in rapid aimed hand movements. *Human Movement Science,* 22, 365-76.

Binkofski, F, Dohle, C, Posse, S, Stephan, KM, Hefter, H, Seitz, RJ and Freund, HJ (1998). Human anterior intraparietal area subserves prehension: a combined lesion and functional MRI activation study. *Neurology,* 50, 1253-9.

Boessenkool, JJ, Nijhof, EJ and Erkelens, CJ (1999). Variability and correlations in bi-manual pointing movements. *Human Movement Science,* 18, 525-552.

Bootsma, RJ, Marteniuk, RG, MacKenzie, CL and Zaal, FTJM (1994). The speed-accuracy trade-off in manual prehension: effects of movement amplitude, object size and object width on kinematic characteristics. *Experimental Brain Research,* 98:535-541.

Brenner, E and Smeets, JB (1996). Size illusion influences how we lift but not how we grasp an object. *Experimental Brain Research,* 111, 473-6.

Burstedt, M, Flanagan, J and Johansson, R (1999). Control of grasp stability in humans under different frictional conditions during multidigit manipulation. *American physiological society,* 2393-2405.

Burstedt, MK, Edin, BB and Johansson, RS (1997). Coordination of fingertip forces during human manipulation can emerge from independent neural networks controlling each engaged digit. *Experimental Brain Research,* 117, 67-79.

Buys, EJ, Lemon, RN, Mantel, GW and Muir, RB (1986). Selective facilitation of different hand muscles by single corticospinal neurones in the conscious monkey. *Journal of Physiology,* 381, 529-49.

Chamberlin , C and Magill, R (1989). Preparation and control of rapid, multisegmented responses in simple and choice environments. *Research Quarterly for Excercise and Sport,* 60:256-267.

Christina, R, Fischman, M, Lambert, A and Moore, J (1985). Simple reaction time as a function of response complexity: Chritstina et al. (1982) revisited. *Research Quarterly for Excercise and Sport,* 56:316-322.

Culham, JC, Danckert, SL, DeSouza, JF, Gati, JS, Menon, RS and Goodale, MA (2003). Visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas. *Experimental Brain Research,* 153, 180-9.

Daprati, E and Gentilucci, M (1997). Grasping an illusion. *Neuropsychologica,* 35, 1577-1582.

De Grave, DDJ, Brenner, E and Smeets, JBJ (2003). Illusions as a tool to study the coding of pointing movements. *In press.*

Donoghue, JP, Leibovic, S and Sanes, JN (1992). Organization of the forelimb area in squirrel monkey motor cortex: representation of digit, wrist, and elbow muscles. *Experimental Brain Research,* 89, 1-19.

Edin, BB, Westling, G and Johansson, RS (1992). Independent control of human finger-tip forces at individual digits during precision lifting. *Journal of Physiology,* 450, 547-64.

Fagergren, A, Ekeberg, O and Forssberg, H (2003). Control strategies correcting inaccurately programmed fingertip forces: model predictions derived from human behavior. *Journal of Neurophysiology,* 89, 2904-16.

Fetz, EE and Cheney, PD (1980). Postspike facilitation of forelimb muscle activity by primate corticomotoneuronal cells. *Journal of Neurophysiology,* 44, 751-72.

Fischman, M (1984). Programming time as a function of number of movement parts and changes in movement direction. *Journal of Motor Behavior,* 16:405-423.

Fischman, M and Reeve, G (1992). Slower movement times may not necessarily Imply on-line programming. *Journal of Human Movement Studies,* 22:131-144.

Fitts, PM (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology,* 47:381-391.

Fitts, PM and Peterson, JR (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology,* 67:103-112.

Flanagan, JR, Burstedt, MK and Johansson, RS (1999). Control of fingertip forces in multi digit manipulation. *Journal of Neurophysiology,* 81, 1706-17.

Flanagan, JR and Tresilian, JR (1994). Grip-load force coupling: a general control strategy for transporting objects. *Journal of Experimental Psychology: Human Perception and Performance,* 20, 944-57.

Flash, T and Hogan, N (1985). The coordination of arm movements: an experimentally confirmed mathematical model. *Journal of Neuroscience,* 5, 1688-703.

Franz, VH, Bulthoff, HH and Fahle, M (2003). Grasp effects of the Ebbinghaus illusion: obstacle avoidance is not the explanation. *Experimental Brain Research,* 149, 470-7.

Franz, VH, Fahle, M, Bülthoff, HH and Gegenfürtner, KR (2001). Effects of visual illusions on grasping. *Journal of Experimental Psychology: Human Perception and Performance,* 27, 1124-44.

Franz, VH, Gegenfürtner, KR, Bülthoff, HH and Fahle, M (2000). Grasping visual illusions: no evidence for a dissociation between perception and action. *Psychological Science,* 11, 20-5.

Gordon, AM, Westling, G and J., cK (1993). Memory representations underlying motor commands used during manipulation of commmon and novel objects. *Journal of Neurophysiology,* 69, 1789-1796.

Guiard, Y (1993). On Fitts's and Hooke's laws: Simple harmonic movement in upper - limb cyclical aiming. *Acta Psychologica,* 82:139-159.

Haffenden, AM and Goodale, MA (1998). The effect of pictorial illusion on prehension and perception. *Journal of Cognitive Neuroscience,* 10, 122-36.

Haffenden, AM, Schiff, KC and Goodale, MA (2001). The dissociation between perception and action in the Ebbinghaus illusion: nonillusory effects of pictorial cues on grasp. *Current Biology,* 11, 177-81.

Helsen, W, Adam, J, Elliott, D and Buekers, M (2001). The one target advantage: A test of the movement integration hypothesis. *Human Movement Science,* 20:643-674.

Hyvarinen, J (1982). Posterior parietal lobe of the primate brain. *Physiology Review,* 62, 1060-129.

Jackson , S, Jackson, G and Rosicky, J (1995). Are non-relevant objects represented in working memory? The effect of non-target objects on reach and grasp kinematics. *Experimental Brain Research,* 102:519-30.

Jeannerod, M (1981). Intersegmental coordination during reaching at natural visual objects. Attention and performance IX. J. Long and A. Baddeley. Hillsdale, NJ:Erlbaum**:** 153-169.

Jeannerod, M (1984). The timing of natural prehension movements. *Journal of Motor Behavior,* 16, 235-254.

Jeannerod, M (1999). Visuomotor channels: Their integration in goal-directed prehension. *Human Movement Science,* 18:201-218.

Johansson, R and Westling, G (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research,* 56:550-564.

Kalaska, JF, Caminiti, R and Georgopoulos, AP (1983). Cortical mechanisms related to the direction of two-dimensional arm movements: relations in parietal area 5 and comparison with motor cortex. *Experimental Brain Research,* 51, 247-60.

Keen, DA and Fuglevand, AJ (2003). Role of intertendinous connections in distribution of force in the human extensor digitorum muscle. *Muscle Nerve,* 28, 614-22.

Kilbreath, SL, Gorman, RB, Raymond, J and Gandevia, SC (2002). Distribution of the forces produced by motor unit activity in the human flexor digitorum profundus. *Journal of Physiology,* 543, 289-96.

Kinoshita, H, Backstrom, L, Flanagan, JR and Johansson, RS (1997). Tangential torque effects on the control of grip forces when holding objects with a precision grip. *Journal of Neurophysiology,* 78, 1619-30.

Lajoie, J and Franks, L (1997). Response programming as a function of accuracy and complexity: Evidence from latency and kinematic measures. *Human Movement Science,* 16:485-505.

Landgren, S, Phillips, CG and Porter, R (1962). Cortical fields of origin of the monosynaptic pyramidal pathways to some alpha motoneurones of the baboon's hand and forearm. *Journal of Physiology,* 161, 112-25.

MacKay, WA (1992). Properties of reach-related neuronal activity in cortical area 7A. *Journal of Neurophysiology,* 67, 1335-45.

Marteniuk, RG, Leavitt, JL, MacKenzie, CL and Athenes, S (1990). Functional relationships between grasp and transport components in a prehension task. *Human Movement Science,* 9:149-176.
Marteniuk, RG, MacKenzie, CL, Jeannerod, M, Athenes, S and Dugas, C (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology,* 41, 365-78.
Mon-Williams, M and McIntosh, R (2000). A test between two hypotheses and a possible third way for the control of prehension. *Experimental Brain Research,* 134:268-273.
Otto-de Haart, EG, Carey, DP and Milne, AB (1999). More thoughts on perceiving and grasping the Müller-Lyer illusion. *Neuropsychologica,* 37, 1437-44.
Paulignan, Y, Jeannerod, M, MacKenzie, C and Martenik, R (1991). Selective perturbation of visual input during prehension movements. 2. The effects of changing object size. *Experimental Brain Research,* 87:407-420.
Pavani, F, Boscagli, I, Benvenuti, F, Rabuffetti, M and Farne, A (1999). Are perception and action affected differently by the Titchener circles illusion? *Experimental Brain Research,* 127, 95-101.
Plamondon, R and Alimi, A (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral and Brain Sciences,* 20:279-349.
Rearick, MP and Santello, M (2002). Force synergies for multifingered grasping: effect of predictability in object center of mass and handedness. *Experimental Brain Research,* 144, 38-49.
Reilmann, R, Gordon, A and Henningsen, H (2001). Initiation and development of fingertip forces during whole-hand grasping. *Experimental Brain Research,* 140:443-452.
Sakata, H, Taira, M, Kusunoki, M, Murata, A and Tanaka, Y (1997). The TINS Lecture. The parietal association cortex in depth perception and visual control of hand action. *Trends in Neuroscience,* 20, 350-7.
Sakata, H, Taira, M, Kusunoki, M, Murata, A, Tsutsui, K, Tanaka, Y, Shein, WN and Miyashita, Y (1999). Neural representation of three-dimensional features of manipulation objects with stereopsis. *Experimental Brain Research,* 128, 160-169.
Santello, M, Flanders, M and Soechting, J (2002). Patterns of hand motion during grasping and the influence of sensory guidance. *Journal of Neuroscience,* 22:1425-1435.
Santello, M, Flanders, M and Soechting, JF (1998). Postural hand synergies for tool use. *Journal of Neuroscience,* 18, 10105-15.
Santello, M and Soechting, JF (2000). Force synergies for multifingered grasping. *Experimental Brain Research,* 133, 457-67.
Savelsbergh, G, Steenbergen, B and van der Kamp, J (1996). The role of fragility information in the guidance of the precision grip. *Human Movement Science,* 15:115-127.
Shinoda, Y, Yokota, J and Futami, T (1981). Divergent projection of individual corticospinal axons to motoneurons of multiple muscles in the monkey. *Neuroscience Letters,* 23, 7-12.
Shinoda, Y, Zarzecki, P and Asanuma, H (1979). Spinal branching of pyramidal tract neurons in the monkey. *Experimental Brain Research,* 34, 59-72.
Smeets, JB, Frens, MA and Brenner, E (2002). Throwing darts: timing is not the limiting factor. *Experimental Brain Research,* 144, 268-74.

Smeets, JB, Glover, S and Brenner, E (2003). Modeling the time-dependent effect of the Ebbinghaus illusion on grasping. *Spatial Vision,* 16, 311-24.

Smeets, JBJ and Brenner, E (1999). A new view on grasping. *Motor Control,* 3:237-271.

Smeets, JBJ and Brenner, E (2001). Independent movements of the digits in grasping. *Experimental Brain Research,* 139:92-100.

Smiley-Oyen, A and Worringham, C (2001). Perhiperal constraint versus on-line programming in rapid aimed sequential movements. *Acta Psychologica,* 108:219-245.

Soechting, JF and Flanders, M (1997). Flexibility and repeatability of finger movements during typing: analysis of multiple degrees of freedom. *Journal of Computational Neuroscience,* 4, 29-46.

Teasdale, N and Smith, R (1991). Deceleration requirements and the control of pointing movements. *Journal of Motor Behavior,* 23:131-138.

Tresilian, J (1998). Attention in action or obstruction of movement? A kinematic analysis of avoidance behavior in prehension. *Experimental Brain Research,* 120:352-368.

von Schroeder, HP and Botte, MJ (1993). The functional significance of the long extensors and juncturae tendinum in finger extension. *Journal of Hand Surgery [Am],* 18, 641-7.

von Schroeder, HP, Botte, MJ and Gellman, H (1990). Anatomy of the juncturae tendinum of the hand. *Journal of Hand Surgery [Am],* 15, 595-602.

Welford, A, Norris, A and Shock, N (1969). Speed and accuracy of movement and their changes with age. *Acta Psychologica,* 30:3-15.

Westling, G and Johansson, RS (1984). Factors influencing the force control during precision grip. *Experimental Brain Research,* 53, 277-84.

Westwood, DA, Chapman, CD and Roy, EA (2000a). Pantomimed actions may be controlled by the ventral visual stream. *Experimental Brain Research,* 130, 545-8.

Westwood, DA, Heath, M and Roy, EA (2000b). The effect of a pictorial illusion on closed-loop and open-loop prehension. *Experimental Brain Research,* 134:456-463.

Westwood, DA, McEachern, T and Roy, EA (2001). Delayed grasping of a Müller-Lyer figure. *Experimental Brain Research,* 141:166:175.

Wing, A and Fraser, C (1983). The contribution of the thumb to reaching movements. *Quarterly Journal of Experimental Psychology,* 35A:297-30

Dankwoord

Eindelijk.

Eindelijk is alles af.

Alles? Nee toch niet.

Er blijft nog een klein stukje te schrijven over. Een klein, maar misschien wel het meest belangrijke stukje. Want het dankwoord is immers het meest gelezen deel van het proefschrift.

De afgelopen ruim 4 jaar heb ik een veelvoud geschreven van de 112 pagina's die voor u liggen. Voor een groot deel te danken aan Jeroen & Eli. In jullie enthousiasme blijven jullie altijd weer blauw of zwart geschreven manuscripten terug geven. Priegelig en met complete routeschema's. Maar helaas moet ik toegeven dat de manuscripten er wel beter van werden. Bedankt dat ik altijd bij jullie naar binnen kon lopen.

Wij zijn twee aio's jij en ik.

Denise, we hebben vier jaar lang vooral veel (hoorbare) lol gehad. Je bent tot steun geweest als ik het niet meer zag zitten met mijn RSI handje, gaf de nodige tips voor het aan de haak slaan van John, haalde me uit een depri-dip bij een mislukt experiment (en ik jou trouwens) en sleepte me voor conditietraining mee naar Het Mannetje. Met jou en Glenn hebben we er twee goede vrienden bij en kunnen we eeuwig heimwee hebben naar Australië.

Beste tuinkabouters en overige oud-bewoners van de 15^{e} verdieping. Hierbij bied ik als nog mijn excuses aan voor mogelijk toegebrachte geluidsoverlast. Bedankt voor de gezellige thee en koffie uurtjes (koekjes!).

John, ik heb al mijn aio- en proefschrift frustraties op je kunnen botvieren. Dat wij elkaar gevonden hebben is het mooiste en beste wat me ooit overkomen is.

Thanks !

Curriculum vitae

Marianne Biegstraaten werd op 26 mei 1976 geboren in Voorburg. In 1994 behaalde zij haar VWO-diploma aan het Interconfessioneel College het Loo in Voorburg. In september van hetzelfde jaar begon zij aan de studie Bewegingswetenschappen aan de Vrije Universiteit in Amsterdam. Zij deed daar onder leiding van Jaap van Diëen onderzoek naar de co-activatie van rompspieren bij een asymmetrische belasting. Verder liep zij stage Mariëlle Stokdijk op de afdeling Orthopedie van het LUMC in Leiden. Ze testte daar een methode om de ligging van de flexie-extensie as in de elleboog te bepalen. Aansluitend daarop schreef ze haar scriptie over de functionele range of motion bij patiënten met reumatoïde artritis.

Na haar afstuderen in 1999 werkte ze een aantal maanden bij NWO-chemische wetenschappen alvorens in augustus 2000 te beginnen aan haar promotieonderzoek bij Jeroen Smeets en Eli Brenner op de vakgroep Fysiologie (nu Neurowetenschappen) in Rotterdam. De resultaten van het onderzoek zijn beschreven in dit proefschrift.

Publications

Articles

Stokdijk M, Biegstraaten M, Ormel W, de Boer YA, Veeger HEJ, Rozing PM. (2000) Determining the optimal flexion-extension axis of the elbow in vivo. A study of interobserver and intraobserver reliability. Journal of Biomechanics 33:1139-1145.

Smeets JBJ, Brenner E, Biegstraaten M. (2002) Independent control of the digits predicts an apparent hierarchy of visuomotor channels in grasping. Behavioural Brain Research 136:427-432.

Biegstraaten M, Smeets JBJ, Brenner E. (2003) Influence of obstacles on the speed of grasping. Experimental Brain Research. 149:530-534.

Biegstraaten M, Smeets JBJ, Brenner E. (2003) Impact force cannot explain the one-target advantage. Human Movement Science 22:365-376.

Biegstraaten M, Smeets JBJ, Brenner E. The relation between force and movement when grasping an object with precison grip. Experimental Brain Research (*submitted*).

Biegstraaten M, de Grave DDJ, Smeets JBJ, Brenner E. The Müller-Lyer illusion: Not a change in length.

De Grave DDJ, Biegstraaten M, Smeets JBJ, Brenner E. Effects of the Ebbinghaus figure on grasping are not only due to misjudged size. Experimental Brain Research (*accepted*).

Refereed abstracts

Biegstraaten M, Smeets JBJ, Brenner E. (2001) The effect of placement of obstacles on a Reach-to-grasp movement. *Eleventh annual meeting on neural control of movement (proceedings)* J-04.

Biegstraaten M, Smeets JBJ, Brenner E. (2001) Can two hypotheses for the control of grasping explain the influence of obstacles on a reach-to-grasp movement? *Nieuwsbrief NVP*, v56,40.

Biegstraaten M, Brenner E, Smeets JBJ. (2002) How do obstacles influence the control of a reach-to-grasp movement? *FENS* Abstr. Vol 1, A193.2.

Biegstraaten M, Smeets JBJ, Brenner E. (2002) Can the one-target-advantage be explained by a difference of the force at impact? Program no 15.*6 Abstract viewer/ Iternary* planner Washington, DC: Society for Neuroscience.

Biegstraaten M, de Grave DDJ, Smeets JBJ Brenner E. (2003) Müller-Lyer and grasping: Illusion or obstacles? *International Conference on Perception and Action XII (proceedings)*, 23.

de Grave DDJ, Biegstraaten M, Brenner E, Smeets JBJ. (2003). The Ebbinghaus figure is more than a size illusion. *International Conference on Perception and Action XII (proceedings)*, 67.

Biegstraaten M, de Grave DDJ, Smeets JBJ Brenner E. (2003) Müller-Lyer: Meer dan een lengteverandering. *Nieuwsbrief NVP*,v33, 32.

de Grave DDJ, Biegstraaten M, Brenner E, Smeets JBJ. (2003) De Ebbinghaus figuur is meer dan alleen een grootte illusie. *Nieuwsbrief NVP*,V34, 33.

Biegstraaten M, de Grave DDJ, Smeets JBJ, Brenner E. (2004) The Müller-Lyer Figure Changes More Than Just The Visual Length. *Fourteenth annual meeting on neural control of movement (proceedings)*, C-5.

Stellingen

1. Indien naar een object bewogen wordt dat tussen obstakels is geplaatst hangt de tijd die nodig is om het object te bereiken vooral af van de afstand tot het dichtstbijzijnde obstakel. Het is onbelangrijk aan welke zijde van het object dit staat (*dit proefschrift*).
2. Illusies zijn niet handig om het gebruik van visuele informatie voor bewegingstaken te onderzoeken (*dit proefschrift*).
3. De contactkracht beïnvloedt de snelheidscurve van zowel een wijsbeweging naar één doel als van een wijsbeweging naar twee doelen achtereen (*dit proefschrift*).
4. De krachten die uitgeoefend worden tijdens de eerste fase van contact van de vinger met het object zijn niet geoptimaliseerd voor het optillen van het object (*dit proefschrift*).
5. De titel van dit project was: "de rol van het contactmoment bij wijzen en grijpen". Achteraf kunnen we concluderen dat -als er al één exact contactmoment te bepalen valt- dit geen rol van belang speelt. (*dit proefschrift*).
6. Taken van het Algemeen Dagelijks Leven zoals het oppakken van een kopje of het schenken met een kan, zijn waarschijnlijk relevanter voor de onderzoeker dan voor de reuma patiënt. (*scriptie*).
7. Goed functioneren is zowel een complex als een subjectief begrip (*scriptie*).
8. Rompspieren zijn actief voorafgaand aan zowel een *verwachte* als een *onverwachte* verstoring van het zwaartepunt bij het tillen van een object (*stage*).
9. Informatie is makkelijker te interpreteren als deze staat waar de lezer het verwacht (*Gopen & Swan, 1990*).
10. Van anti-RSI software raak je gestressed.
11. Als een *ongeluk* in een klein hoekje zit, dat zit *geluk* in de rest.