General introduction
We do it a hundred times a day, yet no man knows exactly how. We can do it in many different ways, yet we prefer a specific way. Every day, we successfully grasp a lot of objects without even thinking about our movements. In this thesis our goal is to partly unravel this masterpiece of human movement control. Studying grasping movements is well suited to gain more insight into human movement control because grasping movements are natural movements that are relatively easy to perform, while to perform them we usually use multiple body parts and sensory systems. To unravel grasping movements, we started off with the question ‘What determines the typical movement patterns of grasping?’ In the literature this question has already been addressed, but the answers are conflicting. In the following paragraphs two popular and highly debated answers are introduced: grasping is simultaneously controlling the transportation of the hand and the size of the grip (Jeannerod 1981) and grasping is simultaneously pointing with multiple fingers (Smeets and Brenner 1999a). In this thesis we chose to focus on these two descriptions of grasping although other descriptions have also been proposed (Rosenbaum et al. 1999a; Rosenbaum et al. 1999b; Rosenbaum et al. 2001; Arbib 1980; Meulenbroek et al. 2001; Simmons and Demiris 2006).

**Grasping is simultaneously controlling the transportation of the hand and the size of the grip**

Jeannerod (1981) examined the relation between the use of visual information related to an object’s extrinsic properties (location, orientation and motion relative to the perceiver) and to its intrinsic properties (shape and size). He did this by studying grasping movements. He hypothesized that independent visuomotor channels exist for processing extrinsic and intrinsic properties of a to be grasped object (target object), and that these channels are activated in parallel and each control a specific part of the arm musculature. Extrinsic target object properties are postulated to activate proximal muscles (e.g., at the shoulder joint) and intrinsic target object properties are postulated to activate muscles of more distal segments (e.g., the digits). In this line of thinking, a grasping movement can be divided in two components, one based on the extrinsic target object properties and dealing with the transportation of the hand (transport component), and the other based on intrinsic target object properties and dealing with forming a properly sized and oriented finger grip (grip component).

To justify the division of a grasping movement in a transport and a grip component neurophysiological findings were brought up (Brinkman and Kuypers 1973; Kuypers 1962; Haaxma and Kuypers 1975) and an experimental study was performed. Jeannerod found that a sudden modification of a target object’s dimensions during the reaching movement affected the grip pattern, while leaving kinematic variables ascribed to the transport component (duration, maximum velocity, and the timing of a landmark in the velocity profile of the wrist) unaltered.
This was interpreted as evidence for the division of a grasping movement into a transport and a grip component. He also found that, for different objects and locations of the target object, the time of maximum grip aperture (the time at which the distance between the index finger and thumb is maximal) was close to the time of a landmark in the velocity profile of the wrist and that from the three subjects in the experiment in which the target object’s dimensions changed, the subject with the least significant effect on the grip pattern made movements of a relatively short duration. These findings led him to propose that the extrinsic information (used to transport the hand) and the intrinsic information (used to control the distance between the digits) are hierarchically ordered: extrinsic information of the target object has priority in determining the overall frame of an action in time and constrains the degrees of freedom open to the use of intrinsic information. A popular description of grasping movements was born.

Since then, various researchers have examined the interdependence of the transport and grip component. Based on the mixed results some argue that the two components are interdependent through a spatial domain (Haggard and Wing 1991; Haggard and Wing 1995), or through a temporal domain (Gentilucci et al. 1992; Hoff and Arbib 1993; Jeannerod 1984; Hu et al. 2005), or both (Saling et al. 1998), or coordinated by a higher order control system (Wang and Stelmach 1998; Jakobson and Goodale 1991). Depending on the relation of the components argued for, additional assumptions were added to the original description of Jeannerod.

**Grasping is simultaneously pointing with multiple fingers**

Smeets and Brenner (1999a) pointed out that the description of grasping proposed by Jeannerod has some shortcomings. To begin with, they argued that a target object can be grasped in various ways because various positions for the digits on the target’s surface lead to a successful grasp. If different positions for the digits are used for grasping objects that are not completely symmetrical, both the final grip size and position of the hand will in general change, while the intrinsic and extrinsic properties of the target object are unaltered. This is in conflict with the idea that the transport and grip component are independent, which was one of the main theoretical arguments for dividing the control of grasping movements into a transport and a grip component.

Smeets and Brenner also argued against the postulation that the transport component results from activating proximal muscles and the grip component results from activating muscles of more distal segments because the distinction between proximal and distal at the level of muscles is not the same as at the level of joints. Movements of the distal joints in the digits are not only made by activating the distal intrinsic muscles of the hand, but also by activating the proximal polyarticular muscles in the lower arm.
Next to this they argued that the definition of the transport component in relation to anatomy is unclear. If one defines the transport component such that the average position of the thumb and finger or the tip of the thumb is being transported (Haggard and Wing 1997; Wing and Fraser 1983; Wing et al. 1986), the transport component depends on the digit’s movement and thus on the grip component. If one avoids this dependence by defining the transport component such that the wrist is being transported, the trajectories of the individual digits cannot be reconstructed from the variables (position of the wrist and grip size) because the position of the grip relative to the wrist is unknown. Two other concerns with transporting the wrist are that the wrist is transported to a position about 15 cm away from the target object in an unknown direction and that the rotation of the wrist becomes part of the grip component while wrist rotations are achieved by activating proximal muscles.

Smeets and Brenner (1999a) proposed an alternative description of grasping without the above-mentioned shortcomings. Their description does not differentiate between intrinsic and extrinsic target object properties or distal and proximal muscles. Instead, they argued that grasping is based on the same principles as pointing and that it can be described as moving the individual digits to preselected goal positions on the target object. Each digit is thus ‘transported’ and the ‘grip component’ is not controlled. The experimental finding that the variability of the thumb’s path and index finger’s path decreases near the target object, whereas that of the wrist remains constant (Paulignan et al. 1997; Haggard and Wing 1997), was taken as support for the control of the individual digits. To deal with natural inaccuracies in human visuomotor control and to avoid slipping, Smeets and Brenner proposed that the digits have the tendency to approach the target object surface perpendicularly and that this tendency is tuned to the constraints of each movement.

To validate their description of grasping, Smeets and Brenner implemented it in a simple two-dimensional minimum-jerk model. Their model predicted that the average of the paths of the thumb and index finger (which is referred to as the transport component in the description of Jeannerod) is independent of the target object’s size and that the size of the grip is independent of the distance of the target object. Their model thus demonstrates that independent behavior of the position of the hand and the distance between the digits does not necessarily mean these variables are controlled independently. The model also correctly predicted various other experimental findings reported in the literature. Based on these findings and the shortcomings of Jeannerod’s description, Smeets and Brenner concluded that grasping behavior is more easily understood in terms of transporting the individual digits than in terms of controlling a transport and a grip component.
An ongoing debate

In the same issue of the journal in which the new view of Smeets and Brenner and their model was presented (Smeets and Brenner 1999a) a lot of commentaries were published (Marteniuk and Bertram 1999; Morasso et al. 1999; Neilson 1999; Newell and Cesari 1999; Rosenbaum et al. 1999b; Savelbergh and Van der Kamp 1999; Steenbergen 1999; Wang and Stelmach 1999; Weir 1999), which were successively discussed by Smeets and Brenner (1999b). The debate was opened.

Since then various experimental studies have been done which dealt with the question which of the two descriptions of grasping is more likely. Some plead for the description of Jeannerod (Van de Kamp and Zaal 2007; Mon-Williams and McIntosh 2000) while others plead for the description of Smeets and Brenner (Smeets and Brenner 2001; Kleinholdermann et al. 2007; Biegstraaten et al. 2003). The experimental results did not lead to general consensus on which description of grasping best describes human grasping movements. Another way to test the credibility of the descriptions of grasping is by building models and comparing their predictions with experimental findings. Both for the description of Jeannerod and for the description of Smeets and Brenner this has been done (Hoff and Arbib 1993; Smeets and Brenner 1999a). Still, the debate continued.

The contribution of this thesis to the debate

A shared limitation of the grasping model based on the description of Jeannerod (Hoff and Arbib 1993) and the grasping model based on the description of Smeets and Brenner (Smeets and Brenner 1999a) is that they (deliberately) only consider movements in an environment without obstacles. Obviously, humans have the capacity to grasp a target object in an environment with obstacles (e.g. grasping a glass of water while a jar of jam is located next to it). Therefore, we think it is useful to have models that are able to deal with obstacles. If the predictions of such a model are in line with human behavior, the model increases the credibility of the description of grasping on which it is based.

We decided to build a model which is able to deal with obstacles and which is based on the description of Smeets and Brenner (Chapter 2). We chose to only model the kinematics of the tip of the thumb and the tip of the index finger and named these points ‘tips’. The following constraints, that are fulfilled by definition, were implemented for each tip: the initial position, the initial velocity, the initial acceleration and the goal position. Next to these constraints, objectives were implemented for each tip. The extent to which objectives influence the movement depends on the situation. We chose to implement objectives that we assumed are necessary for making successful grasping movements: arrive at the goal position at about the same time as the other tip, move not too far from the other tip, move smoothly and do not hit the table, obstacles, the other tip or parts of the target object other than the goal position. We implemented the objectives
by a force field and modeled the tips as point masses. The grasping kinematics then follow from the second law of Newton: the sum of the forces is mass times acceleration. The force field consisted of four forces, each representing one or two of the objectives. To compute each force we had to assume which variables are important for the concerning objective (which distances, velocities, or movement directions) and the relative importance and relation between these variables, the form of the equation.

We tested among other things whether the model was able to reproduce commonly reported characteristics of grasping movements, and whether the model predicts effects of target size, target distance, obstacles, online corrections and initial aperture that are in line with the experimentally found effects reported in literature. In doing so we choose to keep the model’s parameters constant so that predicted features arise from our approach (which is based on the description of grasping proposed by Smeets and Brenner) rather than from parameter fitting. If the model’s predictions are in line with the experimental findings reported in literature, the model increases the credibility of Smeets and Brenner’s description of grasping.

Testing the model’s assumptions

When humans grasp an object off a table, their digits paths curve upward when viewed from the side (e.g. Jeannerod 1981). Descriptions of grasping, including the description of Smeets and Brenner, do not explain this vertical curvature (Jeannerod 1981; Haggard and Wing 1997; Rosenbaum et al. 1999b; Rosenbaum et al. 2001; Smeets and Brenner 1999a). It has been proposed that the vertical curvature is the consequence of considering the table as an obstacle that has to be avoided (Smeets et al. 2010). This is in line with the model’s assumption that humans have the objective to avoid hitting the table (Chapter 2).

We experimentally tested this assumption (Chapter 3) and found that the table did not affect the vertical curvature. This assumption is thus not in line with human behavior. Instead, we found that the vertical curvature could largely be explained by the local constraints imposed by the environment that act only at the very beginning of the movement. Part of the vertical curvature could not be explained by the effects of local constraints imposed by the environment. We wondered whether this part resulted from a strategy to deal with gravity and tested this experimentally (Chapter 4).

That the table did not affect the vertical curvature of the digits surprised us because the digits came quite close to the table when reaching for the target object and it has been proposed that people move so as not to bring body parts within a minimum preferred distance from obstacles (Tresilian 1998). To find out what caused this lack of effect we performed a set of three experiments (Chapter 5). To simultaneously test the form of the model’s equation related to the objective
to avoid contacting obstacles we used two different obstacle dimensions in two of these experiments.

To test the implemented assumption that humans have the objective to avoid contact with the target object at positions other than the goal positions, we collaborated in a study in which the effects of the dimensions of a target block were examined (Chapter 6) and examined the effect of various target object shapes on grasping kinematics (Chapter 7).

In the general discussion (Chapter 8) the contribution of this thesis to the debate, the value of the model of chapter 2 and new insights acquired by testing the model’s assumptions are discussed.