General discussion
The question addressed in this thesis is ‘What determines the typical movement patterns of grasping?’ This thesis does not give a conclusive answer. Instead, it contributes to the answer by supplying some puzzle pieces.

The value of a grasping model

One can make assumptions about the factors that are considered when grasping and how such factors influence the typical movement patterns of grasping. These assumptions can be tested experimentally. That can be done directly, without using any specific model, or with the use of specific models. Using a model is especially valuable when the predicted effects of a certain assumption on grasping kinematics are not obvious so that testing the assumption directly is difficult. A model can be used as a tool to make an assumption testable: predictions of models based on the assumption can be compared with experimental outcomes. Regardless of whether the model predictions are in line with the experimental findings, this increases the insight into the mechanisms underlying the typical movement patterns of grasping by either increasing or decreasing the credibility of the assumption being tested. If the credibility of the assumption decreases this invites an alternative assumption, which again can be tested. In this thesis a grasping model is presented (Chapter 2) and some assumptions that are implemented in it are tested (Chapter 2, 3, 5, 6 and 7). By comparing the model predictions with experimental findings the credibility of certain assumptions increased, while the credibility of other assumptions decreased.

Assumptions of which the credibility increased

There is an ongoing debate as to which description of grasping best describes human behavior. Two highly debated descriptions are: grasping is simultaneously controlling the transport of the hand and the size of the grip (Jeannerod 1981) and grasping is simultaneously pointing with multiple fingers (Smeets and Brenner 1999). This thesis contributes to this debate by testing the assumption underlying the description given by Smeets and Brenner using a model that expands on their assumption (Chapter 2).

This model is able to reproduce many commonly reported characteristics of grasping movements, and predicts qualitative effects of target size, target distance, obstacles, online corrections and initial aperture that are largely in line with the experimentally found effects reported in the literature. The model’s capacity to deal with this whole range of variables and the fact that it gives predictions that are largely in line with the literature increases the credibility of the assumption that grasping can be described as simultaneously pointing with multiple fingers. The model cannot be used to validate alternative descriptions. It therefore supports
the description of Smeets and Brenner but leaves the description of Jeannerod untouched.

When Smeets and Brenner introduced their description they also introduced a simple grasping model based on it. The choice was made not to use their model but to build a new model instead (Chapter 2). The advantages of the new model are that it can deal with obstacles and online corrections and that it accounts for more experimental findings than the model of Smeets and Brenner. The disadvantage is that it is more complex and has more parameters. I therefore recommend using the model of Smeets and Brenner as a first modeling tool and using the model of chapter 2 when the model of Smeets and Brenner cannot deal with the desired situation. The two models are complementary.

One of the assumptions implemented in the model of chapter 2 is that humans have the objective to avoid collisions between their digits and positions on the target object other than the goal positions. Because of this assumption the model of chapter 2 predicts that the shape of the target object has an effect on the relation between object size and maximum grip aperture (Chapter 2), that the maximum grip aperture increases more with object height than with object depth (Chapter 6) and that object shape influences maximum grip aperture (Chapter 7). These predictions are in line with experimental findings, except that experimentally an effect of object depth on maximum grip aperture was not found (Chapter 6). This strongly increases the credibility of the assumption that humans have the objective to avoid collisions between their digits and positions on the target object other than the goal positions.

Another assumption implemented in the model of chapter 2 is that humans have the objective to avoid collisions between their digits and obstacles. Because of this assumption the model predicts qualitative effects of obstacles placed to the side of the target object on movement time, maximum velocity and maximum grip aperture that are largely in line with the experimental findings (Chapter 2). Because of this assumption the model also predicts that the maximum height of the digits increases when moving over an obstacle placed on a table compared to moving over a table without an obstacle, even if the obstacle’s dimensions are chosen such that the obstacle does not obstruct the digits’ paths taken in the absence of the obstacle. This prediction is in line with the experimental findings reported in chapter 5. Together, these findings increase the credibility of the assumption that humans have the objective to avoid collisions between their digits and obstacles.

Assumptions of which the credibility decreased

As already mentioned, one of the assumptions implemented in the model of chapter 2 is that humans have the objective to avoid collisions between their digits and obstacles. As discussed in the previous paragraph, the credibility of this assumption...
umption increased by comparing model simulations with experimental data. To implement this objective in the model additional assumptions had to be made regarding the variables that are important for pursuing this objective and the relative importance and relation between these variables. Stated differently, assumptions had to be made regarding the form of the equation that implements the objective of avoiding collisions between the digits and obstacles. One of these assumptions is that the implementation of this objective depends on the part of the surface area of an obstacle that is visible from the position of the digit’s tip. Because of this assumption, the model predicts that the height of a grasping movement increases with the diameter of a low obstacle placed between the starting position and the target. This was not supported by the experimental findings reported in chapter 5. Therefore the credibility of the implementation of the objective to avoid collisions between the digits and obstacles decreased. An alternative implementation was not tested.

Another assumption implemented in the model of chapter 2 is that the vertical curvature of grasping movements is the consequence of considering the table as an obstacle that has to be avoided (Smeets et al. 2010). This assumption was implemented in the model by the objective to avoid contacting the table. Experimentally it was found that the table did not affect the vertical curvature (Chapter 3). This disproves the implemented assumption. Therefore an alternative assumption that would explain the vertical curvature was searched for. Experimentally it was found that the vertical curvature could largely be explained by the local constraints imposed by the environment at the very beginning of the movement (Chapter 3). However, the effects of local constraints imposed by the environment could not explain all of the vertical curvature. Whether the remaining part resulted from a strategy for dealing with gravity was experimentally tested in chapter 4. It was found that gravity affects the vertical curvature by pulling the digits downward. However, this finding only partly explains the unexplained part of the vertical curvature. Further research is needed to find which other factors contribute to the vertical curvature.

It is remarkable that the assumption that the vertical curvature of grasping movements is the consequence of considering the table as an obstacle that has to be avoided was not supported by the experiments reported in chapter 3, 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). A better understanding of this discrepancy was obtained by performing an experimental study (Chapter 5) in which it was found that obstacles below the starting position do not influence grasping kinematics when the constraints at the start are such that the digits curve upward. This might be because not taking obstacles into account in a region that one is not likely to enter, such as below the starting position if one starts by moving upwards, reduces the computational burden.
Untested assumptions

Several assumptions that are implemented in the model of chapter 2 were not tested in this thesis. These are that humans have the objective to let their digits arrive at the goal position at about the same time, keep the distance between their digits within a certain limit, avoid collisions between their digits and move smoothly. From a biomechanical point of view it is likely that humans have the objective to let their digits arrive at the goal position at about the same time. If there is a large time difference between the arrivals of the digits, unstable objects will easily be knocked over. The objective to keep the distance between the digits within a certain limit makes sense from an anatomical point of view. The length of the digits and the range of motion of the concerning joints determines the maximum distance between the digits.

The objective to avoid collisions between the digits and to move smoothly both seemed logical to me because the digits do not often collide with each other while grasping and the digit’s paths are usually smooth. However, this might also be the consequence of other objectives. Therefore I am not sure whether this behavior itself is the goal, or whether it is the by-product of another aim. More research is needed to clarify this issue.

Model parameters

The goal of the model of chapter 2 is to gain more insight into grasping kinematics, not to replicate grasping movements. Therefore the focus was on the model’s qualitative predictions. A sensitivity analysis showed that selected features of the movement can be controlled by changing the parameter values without changing the model’s general behavior (Chapter 2). In this thesis I aimed to keep the values of the parameters constant across studies. This choice was made because I wanted to show that the predictions were the result of the assumptions implemented in the model and not of parameter fitting. Unfortunately, I misinterpreted a sentence in the study of Jeannerod (1981), concerning the timing of a specific point in the velocity profile of the hand, that was used to choose the values of the model’s parameters. To test whether this misinterpretation influenced the conclusions about the credibility of the implemented objectives I ran all simulations reported in this thesis again with a different set of parameter values (not reported in this thesis). I choose this new set of parameter values based on the study of Saling et al. (1998) and not on the study of Jeannerod (1981) because in the study of Saling et al. the timing of the maximum grip aperture and of the maximum velocity were clearly reported while in the study of Jeannerod they were not. The new parameter values led to different quantitative predictions. Some predictions are closer to the experimental data and some are further away. However, the qualitative predictions barely changed and therefore the model predictions using the new set of param-
eters still lead to the same conclusions about the credibility of the implemented objectives.

**Conclusion**

The model of chapter 2 increases the credibility of the view that grasping can be described as two times pointing. Testing the model’s assumptions by comparing its predictions with experimental data led to new insights into what determines the typical movement patterns of grasping.