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RESEARCH NOTE

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Does a complex model help to understand grasping?

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Abstract Several studies have demonstrated a peculiar effect of initial aperture on the grip formation in reach-to-grasp movements. We compare these findings with the predictions of two models for prehension. The first is a very simple model that only describes the movements of the end-effectors. The second model is rather complex and takes postural constraints into account. Both models can account for many aspects of human grasping when the movement starts with the digits in contact. We compare the models' performance with published data on other initial configurations. Both models predict an effect of initial aperture that was not present in the data. The model that considers postural constraints does not perform better than the simple model. We conclude that such constraints are not responsible for the main characteristics of the reach-to-grasp movement.

Keywords Human · Prehension · Posture · End-effector · Model

Introduction

In a recent paper, Meulenbroek et al. (2001) tested a model for grasping which we will refer to as the posture model (Rosenbaum et al. 2001). They showed that the model could describe various experimental findings in the literature on grasping quite well. Performance was comparable with that of an earlier model, which we will refer to as the end-effector model (Smeets and Brenner 1999). Both models are based on the idea that trajectories are formed in such a way that, given a certain amount of variability in the movement, there is a good chance to end at the desired position. Both models have been applied only to two (horizontal) dimensions of the movement. A difference between the models is their complexity.

The end-effector model is limited: it only describes the movements of the end-effectors, the tips of thumb and index finger, ignoring the underlying movements of the joints. This limitation means that it can only take constraints at the level of the end-effector into account. The consequence is that it can predict movements that are not feasible anatomically because of impossible postures or collisions of part of the hand or arm with the object. This limitation is at the same time its strength: we know exactly what causes the model's behaviour. This is so because the model is very simple: it has only one (task-related) parameter, and the predictions can be made analytically. Thus, if the model predicts certain behaviour, we can be certain about the origin of each aspect of that behaviour.

The posture model is a more elaborate description of human behaviour. It describes the movements of all the joints (only around vertical axes), which is essential if the purpose of the model is to predict *how* grasping movements are made. The model's behaviour is based on anatomical constraints and obstacle avoidance, so it will always predict movements that are feasible anatomically. The disadvantage of the posture model is that it is quite complex. For instance, it has more than 25 parameters describing anatomical details of the arm. It is not clear how sensitive the model is for the choice of these parameters. Moreover, it has more than 10 "free" parameters describing the assumed relative importance (cost factor) of the various joints and simulation constants. This complexity is a disadvantage if the purpose of the model is to understand *why* humans grasp as they do. Moreover, analytical predictions are not possible with this model.

The present study uses the difference between these two models to try to determine the origin of grasping behaviour. If the additional complexity of the posture model is needed to adequately predict the movement of the end-effector, we can conclude that one of the added aspects is important in grasping. If not, we can conclude that only the constraints on the end-effector are critical.

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We compare the predictions of the two models for the experimental results in Meulenbroek et al. (2001). In these experiments, the participants started the reach-to-grasp movements with their hand already opened, a paradigm introduced by Stelmach and colleagues (Saling et al. 1996; Timman et al. 1996). Neither model needed specific changes to deal with these conditions.

Materials and methods

We did not perform new experiments to test the models, but used the experimental results published in Tables 2, 3, and 5 of Meulenbroek et al. (2001). Following their presentation of data, we used the extra aperture (difference between maximum grip aperture and object size) as a measure for the aperture. In this way, averaging over object sizes can give interpretable results. From their Tables 2 and 3 we used the pooled mean of extra aperture and of the time to maximum aperture. In addition to these values, we calculated a weighted average of the individual subjects' slopes of the regression analyses relating maximum aperture to object size provided in their Table 5, using the R^2 values as the weights.

For comparing the two models with these experimental data we have to choose adequate values for the parameters in the models. For the posture model, we did not perform any simulations, but just used the results published in Tables 2–4 of Meulenbroek et al. (2001). The parameters used in that paper were not chosen on the basis of an explicit optimisation of their model's performance. However, they were not the same as those used in the original paper on that model either (Rosenbaum et al. 2001). For instance, the cost of movements of the joints of the hand were six times lower than those of more proximal joints, whereas the costs were equal in the original paper. We made no attempt to evaluate the role of these parameters.

The predictions of the end-effector model are straightforward. According to this model, only the difference between the initial and final position of each individual digit is relevant. As long as the orientation of the grip does not change during the movement, a larger initial aperture is therefore equivalent to a smaller object. The Eqs. 6 and 7 in the appendix of Smeets and Brenner (1999) are derived for the end-effectors initially in contact. They can easily be rewritten for an object with diameter d and an initial hand aperture d_0 (provided that the grip's orientation does not change). The model predicts that the hand should open to a maximum

$$grip_{\max} = d_0 + \left(\frac{3\,(a_p + 10(d - d_0))}{5\,(a_p + 6(d - d_0))}\right)^4 \left(\frac{4}{15}a_p + d - d_0\right) \tag{1}$$

at relative time t_r (t_r=0 is movement onset; t_r=1 is the end of the movement)

$$t_r = \frac{3\,(a_p + 10(d - d_0))}{5\,(a_p + 6(d - d_0))} \tag{2}$$

These equations have only one free parameter, the approach parameter a_p. One can estimate its value on the basis of the intercept of the regression of maximum grip aperture against object size when starting with the hand closed [Eq. (1) with d=d_0=0]. We chose a value of a_p=0.75 m, which corresponds to an intercept for the regression of about 2.7 cm. This value for the intercept is close to averages of the intercept for the smallest object of both model and experimental results (Tables 4 and 5 of Meulenbroek et al. 2001). Using this value for a_p, we predicted the maximum aperture and its timing for each of the nine experimental combinations of object size and initial aperture.

The end-point model makes clear predictions. Equation (2) shows that hand aperture will have a maximum before object contact (t_r<1) as long as the initial aperture d_0 is less than a_p/10 larger than the object diameter d. Otherwise (d_0–d>7.5 cm, which never occurred in the experiment) the grip will not have a maximum during the movement, and the hand will gradually close around the object. The condition closest to this interesting situation is the movement towards a 0.3-cm object starting with a grip aperture of 7 cm.

Results

An overview of the experimental and model grip aperture functions for grasping movements starting with a 7-cm-wide opened hand are plotted in Fig. 1. Neither model predicts the experimentally observed closing and reopening of the hand.

Both models predict the same behaviour for the extra aperture as a function of initial aperture (Fig. 2A). The predicted increase with initial aperture is much stronger than that observed experimentally. Similar results are found for the timing of the maximum aperture: both models predict that the time to peak aperture should decrease much more rapidly with initial aperture than was experimentally found (Fig. 2B). Following Meulenbroek et al. (2001, Table 4), we also analysed the effect of initial aperture on our model's predictions for the slope relating maximum aperture and object size (Fig. 2C). We found that the slope decreased with initial aperture (from 0.82 to 0.44), which is almost as strong as the predictions of the posture model (from 0.78 to 0.34). In contrast with both models, the participants in Meulenbroek et al. (2001) did not show a clear effect of initial aperture on this slope (a decrease from 0.76 to 0.75).

In summary, the two models predict a very similar effect of initial aperture on the reach-to-grasp movement. This predicted effect differs clearly from what humans do.

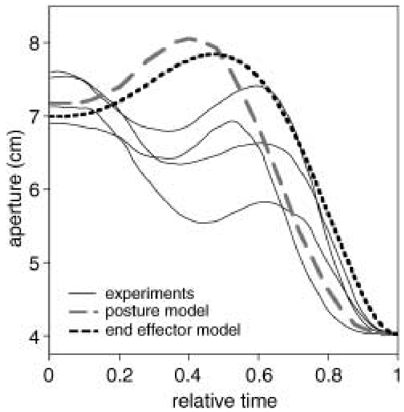

Fig. 1 The hand aperture is plotted as a function of normalised time for grasping with an initial hand aperture of about 7 cm. *Thin curves* Data of four participants replotted from Fig. 10 of Meulenbroek et al. (2001). *Thick dashed curve* Predictions of the posture model (replotted from Fig. 4D of Meulenbroek et al. (2001). *Thick dotted curve* Predictions of the end-effector model. We aligned all curves so that the final aperture matched the actual object size

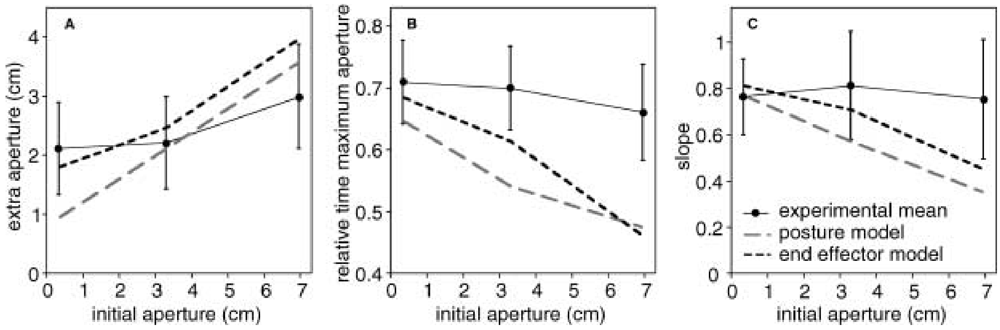

Fig. 2A–C Comparison of the end-effector model with the posture model and the experiment of Meulenbroek et al. (2001). **A** The difference between maximum hand aperture and object size, averaged over object sizes. **B** The time of maximum aperture as a percentage of the movement time, averaged over object sizes. **C** The slope of the regression of maximum aperture as a function of object size. The data for the end-effector model are the result of our calculations. The data for the posture model and the experimental data are from Tables 2 (in **A**), 3 (in **B**), and 4 and 5 (in **C**) of Meulenbroek et al. (2001). In **A** and **B** the *error bars* indicate standard deviations across subjects and object sizes. In **C** the *error bars* indicate standard deviations across subjects. Despite its simplicity, the end-effector model explains the data no worse than the much more complex posture model

Discussion

One aspect of the data deserves some discussion. The peaks of the grip aperture of the posture model and the experimental data in Fig. 1 are different from the values of the corresponding points in Fig. 2A, B. This is not an error of our redrawing, but is caused by differences in the sequence of segmenting, averaging and taking medians in the original paper (R.G.J. Meulenbroek, personal communication). This shows that one should be very cautious when comparing absolute values of grasping parameters from different studies with each other and with model predictions. Differences between published values of parameters might reflect variations in data analysis rather than differences in behaviour.

The similarity between the predictions of the two models is very important for our understanding of the behaviour of the (rather complex) posture model. The results of the posture model do not explicate which constraints are causing the observed model behaviour. For instance, the slope of the relation between maximum grip aperture and object size is 1.00 in the original simulations of Rosenbaum et al. (2001). One can bring this value close to the observed human behaviour (slope 0.8) by reducing the number of possible postures (grain of the simulations; Table 2 in Rosenbaum et al. 2001). Another way to reduce this slope is to reduce the expense factor of the digits' joints (compare Meulenbroek et al. 2001 with Rosenbaum et al. 2001). So the posture model leaves us with two possible explanations of the experimental observation: either the number of evaluated postures is limited or movements of digits are less expensive than those of an arm.

Smoothness of the movement and perpendicular approach are the sole determinants of the end-effector model's behaviour. Although the end-effector model neglects all anatomical constraints present in the posture model, it yields very similar results. We assume that in the posture model, obstacle avoidance leads to perpendicular approach and movement cost to smooth movement. We conclude therefore that the internal postural constraints play a negligible role in trajectory formation in the posture model of grasping. This conclusion helps us to understand the behaviour of the posture model, but as human behaviour differs from the models' predictions, it does not tell us anything about human behaviour.

The systematic difference between the performance of the two models and the experiments is important for understanding grasping. Experiments (Meulenbroek et al. 2001; Saling et al. 1996; Timman et al. 1996) consistently show that if one starts a reach-to-grasp with the hand open wider than the object, it closes and reopens during the movement. Neither the posture model nor the end-effector model predicts this behaviour. Both models take into account the constraints of the object, and the posture model also considers various anatomical constraints. The additional elements in the posture model did not lead to a better performance. One might conclude that this model has formalised the constraints in a wrong way. For instance, giving one or several parameters another value could improve performance. Alternatively, the cost-function could be suboptimal, and one might also want to attribute costs to the postures themselves (Cruse and Bruwer 1987). However, the fact that the final hand orientation is independent of the arm posture (Roby-Brami et al. 2000) and that grasping behaviour is independent of the effector used [it is the same for grasping with the mouth (Castiello 1997) or prosthetic hand (Wing and Fraser 1983)] argue against an important role of posture itself.

Another possible conclusion is that the observed behaviour is caused by factors neglected in both models, such as dynamic interactions between body segments (Hollerbach and Flash 1982). The experimental results of Kritikos et al. (1998) indicate two other factors that are neglected by the models: the three-dimensional nature of the task and contact forces at movement onset. By using four initial postures, Kritikos et al. (1998) showed that the main difference between the two initial aperture conditions is not the initial aperture itself, but the orientation of the arm and hand. This could be a pure postural constraint in more than two dimensions, but could also be due to forces exerted at the table at the onset of movement. These two explanations each suggest that an extension of the models to three dimensions could help to model the observed effect of initial aperture. For the posture model, this would imply modelling 3-D rotations at the joints, which is a rather complicated exercise. For the end-effector model, an extension to three dimensions is very straightforward. Moreover, additional constraints on the acceleration at movement onset could be included to model the contact forces at the table.

Meulenbroek et al. (2001) made four qualitative predictions for the reach-to-grasp movement on the basis of their posture model. Two predictions concerned the effects of object size on the timing and magnitude of the maximum hand aperture. These were qualitative formulations of the quantitative predictions made by the end-effector model of Smeets and Brenner (1999). The third prediction of Meulenbroek et al. (2001) is that “objects located to the right of the body midline should elicit large, biphasic, shoulder and elbow rotations”. This prediction is beyond the realm of the end-effector model, as there are no joints in it. However, this model predicts a straight movement of the hand to the target. The geometry of the arm makes it impossible to perform these without the observed movements of the elbow and shoulder (Morasso 1981; Sergio and Scott 1998). The fourth prediction was that “grasping kinematics should be differentially affected by initial aperture”. Our present results show that the end-effector model yields an equivalent prediction, but that these predictions are not very close to human behaviour.

Using a more complex model (i.e. the posture model instead of the end-effector model) did not yield a better prediction of human grasping behaviour. Adding complexity is only useful if the explanatory power of a model is increased. For the present comparison of models for grasping (posture versus end-effector) this is definitely not the case, so one might think that the answer to the question in the title of the present paper is simply “no”. However, as adding postural constraints did not yield a better performing model, our understanding of grasping is improved. We now know that postural constraints, formulated as the cost of movement by Meulenbroek et al. (2001), are not important in the trajectory formation of the reach-to-grasp movement.

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