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RESEARCH NOTE

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A model of the coupling between grip aperture and hand transport during human prehension

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Abstract It has been repeatedly demonstrated that the opening between the index finger and thumb (grasp component) during an object-directed reach-to-grasp movement achieves maximum aperture approximately two-thirds of the way through the duration of the reaching movement (transport component). Here we offer a quantitative model of the temporal coupling between grip aperture and wrist velocity which shows experimentally that the correlation between grip aperture and object size is a sigmoidal function of movement duration. When wrist velocity reaches its peak value, the correlation between the grip aperture and the size of the goal object has reached half of the correlation that is achieved by the end of the movement.

Keywords Prehension · Transport and grasp components · Model · Temporal coupling · Grip aperture · Wrist velocity

Introduction

The control of manual prehension requires information not only about the spatial location of the goal object, but also about its size, shape, and orientation. Traditionally, manual prehension (before contact with the object) is thought to consist of two components: a transport component in which the hand is carried toward the goal object and a grasp component in which the fingers and hand are pre-shaped in anticipation of contact with the goal object (Jakobson and Goodale 1991; Jeannerod 1984).

Jeannerod (1984) showed that the velocity of the transport component (as measured by wrist velocity) has a bell-shaped profile. During movement, the grasp component (as measured by grip aperture between the index finger and thumb in a precision grip task) reaches maximum aperture approximately two-thirds of the way through the duration of the reaching movement. This relationship holds over a range of different distances and object sizes. In short, wrist velocity and grip aperture are temporally coupled as the hand moves toward the goal object.

Early on, Jeannerod (1981) argued that even though the two components of prehension were tightly coupled, each was sensitive to different properties of the object. The transport component, he argued, was scaled according to the distance of the goal object whereas the grasp was scaled according to the size of the goal object. Since Jeannerod's original observations, others have suggested that this distinction may not be as clear-cut as was originally thought (e.g., Jakobson and Goodale 1991; Servos et al. 1998; Smeets and Brenner 1999). But whatever the case may be, it is clear that the two components must be coordinated as the reaching and grasping movement unfolds.

Here we offer a model of this coupling showing that a single non-linear mathematical function captures the relationship between transport and grasp. When participants picked up rectangular objects of different sizes, the changing correlation between grip aperture and object size as the movement unfolded was shown to be a sigmoidal function of movement duration (as measured by the percentage time of the whole duration).

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According to this function, the correlation between the grip aperture and the size of the goal object at peak wrist velocity is half of the value that it finally achieves at the end of the movement.

Methods

Eight participants were tested[1]. All were strongly right handed, as determined by a modified version of the Edinburgh handedness inventory (Oldfield 1971). Participants had normal or corrected-to-normal vision, with a stereoacuity of at least 40 min. arc as determined by the Randot Stereotest (Stereo Optical, Chicago, IL, USA). Infrared light-emitting diodes (IREDs) were attached to the fingernails of the thumb and index finger of the right hand. A third IRED was attached to the left side of the wrist opposite the styloid process. The spatial position of each IRED was recorded by three OPTOTRAK systems (Northern Digital Inc., Waterloo, Canada) at a sampling frequency of 100 Hz.

On a given trial, participants were requested to use their fingers to pick up an object positioned in front of them on a white working surface. Participants were seated in front of the work surface and were instructed to rest their right hand flat on the working surface with the thumb placed on a start position immediately in front of the torso at their midline. The goal object was centered at this midline. As shown in Fig. 1, the long axis of the goal object was perpendicular to this midline. The far edge of the goal object was placed 35.0 cm from the start position. Participants were instructed to reach out and pick up the object in a "natural and comfortable" manner.

A verbal command of "go" signalled the initiation of a grasping movement. Simultaneously, the OPTOTRAK systems were triggered to record the movement. An extra IRED was embedded in the working surface below the object. When participants picked up the object using their fingers, one of the three OPTOTRAK systems could view the IRED. This marked the end of a trial and the OPTOTRAK systems stopped their recording. The experiment was carried out in closed loop, in which participants could view their hand and the object during reaching and grasping movements.

Nine rectangular objects were used in the experiment. As illustrated in Fig. 1, these objects varied in width (from 3.0 to 6.0 cm) and length (from 10.0 to 20.0 cm). Each object was 1.0 cm in height. Each participant performed several practice trials to become familiar with the requirements of the task. During testing, each participant performed 36 trials (four replications with each object). The order of the objects was randomized from trial to trial. Only trials for which complete data were available for reaching and grasping components were included in the analysis. Less than 3% of the trials were eliminated using this criterion. Although participants did not receive any instruction about how to pick up the goal object, all participants consistently grasped the goal object across its width.

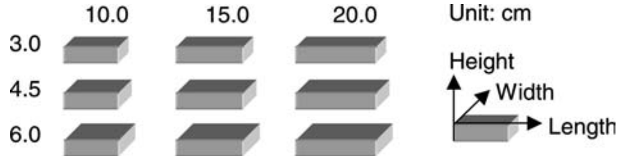

Fig. 1 Description of goal objects

Results and discussion

Based upon the observations in previous studies, the relationship between the grip aperture and the size of an object can be expressed as a linear regression from experimental data as:

$$A(t) = a(t)W + b(t) \qquad (1)$$

where $A(t)$ represents the grip aperture at instant t and is computed from recorded spatial positions of the thumb and index finger; and W is the width of the object. The coefficients a(t),b(t), and the square of the correlation coefficient (R^2) were calculated by the least-squares error method. The value of R^2 (normally between 0 and 1) represents how well grip aperture is matched to the size of the goal object. If $R^2 = 0$, the grip aperture does not match the size of the goal object at all. Conversely, the relation of $R^2 = 1$ indicates a perfect correspondence between the grip aperture and the size of the goal object. Because the size of the goal object is a constant during a grasping movement, the change of the value of R^2 reflects the change of the grip aperture, as reflected in the linear relationship depicted in Eq. 1. In other words, the value of R^2 maps the grip aperture onto the size of the goal object. This mapping scales the grip apertures of different participants, who have different hand sizes, into one uniform range from 0 to 1. The advantage of this mapping is the convenience of describing the grip aperture independent of hand size. For this reason, we selected the correlation coefficient R^2 as a parameter to examine the coupling between grasp and transport components.

In our experiment, participants were instructed to place their hands flat before initiating movements and to pick up a goal object in front of them with their fingers. Thus, it was expected that subjects would show a low-correlation between the grip aperture and the size of the goal object at the beginning of movements and a high-correlation at the end of movements. Nevertheless, the question remains as to how this trend can be described quantitatively. To examine this trend, we plotted the value of R^2 during reaching and grasping movements in Fig. 2. The movements are normalized against the entire

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[1] The study was conducted at ATR Computational Neuroscience Laboratories, Soraku-gun, Kyoto, Japan, and followed the ethic guidelines at the facility. All participants gave their informed consent prior to their inclusion in the study

movement duration. Solid lines represent experimental data – the mean value of R^2 for each participant. The asterisked line is the averaged value of all participants. In general, participants demonstrated that the correlation between their grip aperture and the size of the goal object followed a curve, which consists of three phases. The first phase is the first 30% of movement duration. In this phase, the correlation coefficient R^2 remains at a low value in a shallow slope. The second phase runs from 30 to 60% of movement duration, during which the correlation coefficient R^2 increases dramatically with a steep slope. In the remaining third phase, the correlation coefficient R^2 increases very slowly until it reaches its maximum value at the end of the trial when the hand holds the goal object. Again, this slow increase has a shallow slope. Mathematically, these characteristics of the curve are similar to those of a sigmoidal function. Thus, we propose that a useful way of describing the change in the correlation between grip aperture and object size over the entire movement is the following sigmoidal function:

$$R^2 = \frac{\alpha}{1 + \mathrm{e}^{-\beta(t - t0)}} \tag{2}$$

where α represents the maximum value of R^2, β is a positive coefficient, t represents the percentage time of the movement duration, and t_0 is a constant of the percentage time at which the value of R^2 is the half of its maximum. It is worth noting here that the definition of t_0 arises from the change of the correlation between grip aperture and object size without taking into account the change in wrist velocity when the hand moves towards the goal object. The coefficients α, β, and t_0 can be acquired through the non-linear fitting of experimental data with Eq. 2.

By the Gauss–Newton method, the non-linear least-squares fitting of the experimental data with Eq. 2 yielded the coefficients $\alpha = 0.8671$, $\beta = 0.0887$, and $t_0 =$ 36.5657 (%). The confidence interval of this fitting is 95%. In Fig. 2, the line of open circles represents the "calculated R^2" from Eq. 2 using these coefficients.

Previous studies on prehension have found that peak wrist velocity is achieved during the first half of movements, in the range from 30 to 50% of movemnt duration (e.g., Hu et al. 1999). Indeed, the coefficient $t_0 =$ *36.5657* (%) in Eq. 2 is within this range, even though the definition of t_0 was not made on the basis of this observation. Thus, it was of interest to know whether t_0 differs from t_p—the percentage time at which peak wrist velocity is reached. An ANOVA confirmed that t_0 does not differ statistically from t_p (mean value: $t_0 =$ *36.5657*%, $t_\mathrm{p} =$ *35.8622*%; $F = 0.3013$, $P > 0.05$). Consequently, Eq. 2 can be rewritten as Eq. 3, in which t_p replaces t_0 as follows:

$$R^2 = \frac{\alpha}{1 + e^{-\beta(t - t_\mathrm{p})}} \tag{3}$$

Using the same coefficients $\alpha = 0.8671$ and $\beta = 0.0887$, Fig. 3 shows two sigmoidal curves. The curve with open circles was calculated from Eq. 2 for $t_0 = 36.5657\%$ and the curve with filled circles was calculated from Eq. 3 for $t_\mathrm{p} = 35.8622\%$. As shown in Fig. 3, the two computed sigmoidal curves are in good agreement with each other, indicating that the sigmoidal function in Eq. 3 describes the correlation between the grip aperture of the hand and the size of rectangular objects.

According to the characteristics of a sigmoidal function, the value of R^2 in Eq. 3 at the percentage time t_p should be equal to half of the value of R^2_end at the end of movement duration. To verify this using the observations of the participants' actual performance, a comparison was carried out between t_p and the percentage time t_half when the half value of R^2_end was achieved. Analysis revealed that the mean values of t_half and t_p were 35.4750 and 35.8622%, respectively. An ANOVA analysis showed that the mean values of t_half and t_p do not differ

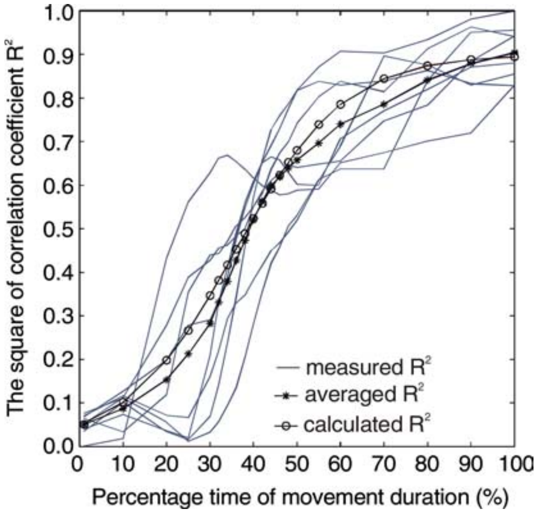

Fig. 2 The square of correlation coefficient R^2 vs. the percentage time of movement duration

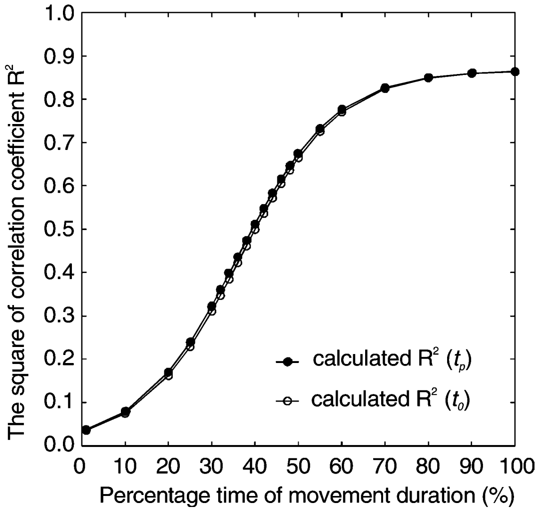

Fig. 3 Agreement of Eq. 2 and Eq. 3

from one another ($F = 0.01476$, $P > 0.05$). In other words, the half value of R^2_{end} is achieved at the same time as peak wrist velocity, when movement duration is normalized. Thus, Eq. 3 (by means of the parameter t_p) captures the temporal coupling of the transport and grasp components of prehension.

The neural mechanisms (and the characteristics of the physical plant of the arm and hand) that underlie the sigmoidal function shown in Fig. 3 are poorly understood. Nevertheless, by providing a quantitative model of the temporal coupling between the transport and grasp components of prehension, any manipulations of the variables contributing to this coupling can be more easily studied and evaluated.

Several models of prehension have been put forward, only some of which have incorporated the notion that the transport and grasp components are separable but coupled (Jeannerod 1984). Harris and Wolpert (1998) have put forward a minimum-variance account of how movement trajectories (including goal-directed arm movements) are selected. Their model, however, does not address how the grasp component is integrated with the arm movement. Hoff and Arbib (1993) have modeled how the two components of prehension are organized. They have proposed that a "preshape controller" determines the grasp component in conjunction with a "hand-closure controller". Nevertheless, their model requires the postulation of additional constraints on how the two components are coupled. Mon-Williams and Tresilian (2001) have recently proposed a "rule of thumb" principle, in which they argue that the durational ratio of the opening and closing phases of grip aperture is proportional to the ratio of maximum grip aperture and the size of the goal object. This "rule of thumb" is simple and plausible, but predicts a time of maximum grip aperture that is much earlier than is typically observed in empirical studies. Smeets and Brenner (1999) do not deal with the temporal coupling of transport and grasp, but instead put forward a model that uses a minimum-jerk approach to predict how experimental variables such as object size, reaching velocity, fragility, and required accuracy influence the timing and amplitude of the maximum grip aperture. In their model, the thumb and index finger are treated as relatively independent effectors. Recently, Cuijpers et al. (2004) have studied the relation between object shape and grasping kinematics. One of their observations shows that the correlation coefficient of grip aperture has a linear relationship with respect to the percentage of movement distance. Because this study did not provide information about wrist velocity, it is impossible to infer the relationship between the correlation coefficient of grip aperture and movement duration.

To gain insight into the determinants of prehension, Meulenbroek et al. (2001) and Rosenbaum et al. (2001) have conducted computer simulations of grasping based upon their theory of posture-based motion planning, which hypothesizes that the planning of grasping movements entails constraints including obstacle avoidance and reducing movement-related effort. They reported that their simulations can accurately mimic the characteristics of the transport and grasp components of prehension that have been observed in earlier experimental studies, for example, the time course of grip aperture and wrist velocity during grasping movements. However, their simulations did not attest the temporal coupling between these components.

As discussed above, none of these models/theories can deal adequately with the observed temporal coupling between the transport and grasp components of prehension. One reason for this is that no one has experimentally examined in detail this type of coupling between the two components. The present study has shed some light on this issue. The sigmoidal function in Eq. 3 describes not only the correlation between grip aperture and object size during the entire duration of the reaching and grasping movement, but also the temporal coupling of the transport and grasp components. The critical parameter here is t_p, the point in time where wrist velocity reaches its peak value. Thus, when the wrist velocity (transport component) reaches its peak value, the correlation between grip aperture (grasp component) and the size of the goal object is at half the value it achieves when the hand picks up the object.

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