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Robust movement segmentation by combining multiple sources of information

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ABSTRACT

One of the first steps in analyzing kinematic data is determining the beginning and end of movement segments. This is often done automatically on the basis of one parameter (such as a speed minimum) and subsequently corrections are made if visual inspection of other kinematic parameters suggests that the obtained value was incorrect. We argue that in many cases it is impossible to find a satisfactory endpoint for all possible movement segments within an experiment using a single parameter because the intuition about the end of a segment is based on multiple criteria. Therefore by taking the maximum of an objective function based on multiple sources of information one can find the best possible time point to call the endpoint. We will demonstrate that this Multiple Sources of Information method (MSI-method) for finding endpoints performs better than conventional methods and that it is robust against arbitrary choices made by the researcher. Using it reduces the chance of introducing biases and eliminates the need for subjective corrections. Although we will take goal directed upper limb motion as an example throughout this paper, it should be stressed that the method could be applied to a wide variety of movements.

1. Introduction

When a subject is asked to make a movement (such as to pick up an object, place it somewhere and move the hand back to the starting position; Fig. 1), he makes a more or less continuous movement within which one can often identify several segments (such as reaching for the object and grasping it, lifting it and moving it to the target position, and finally releasing it and moving the hand back). In the analysis of kinematic data, one of the first steps is to determine the beginning and the end of such movement segments. In the literature, one can find a wide variety of ways to determine their boundaries. This variety reflects the fact that there is no obvious way to define such boundaries especially when segment boundaries do not coincide with a stationary posture. We argue that the reason for the difficulty of coming up with a general definition is that there is often no unambiguous endpoint of a movement segment. Despite there being no unambiguous segment endpoint, people do have intuitions about how a movement should be segmented into its parts. Some of the criteria that are used to segment grasping movements are summarized in Table 1.

Exactly how one chooses to segment the different parts of the movement might seem arbitrary as long as it is done consistently, but the differences between the different methods can be quite large. To illustrate this, we segmented the data of the prehension study depicted in Fig. 1 using three conventional segmentation methods taken from the literature. In the study, subjects had to reach from a start position towards a sphere that was placed in one of twenty-one possible locations. They had to grasp the sphere and move it towards a specified place position. Fig. 1 depicts a trial where the start position was near and the place position was far. There were also trials where the start position was far and the place position was near. We want to determine the end of the initial reach-to-grasp segment that is indicated by the thicker curves in Fig. 1.

The three conventional methods we used to segment the data were the first time the velocity of the *thumb* marker fell below 5 cm/s (Dijkerman et al., 2008), the first time the *aperture* stopped decreasing (Paulignan et al., 1997; thumb and index finger data were filtered with a forward and reverse pass of a second-order Butterworth filter with a cutoff frequency of 10 Hz), and the first minimum following the peak velocity of the *wrist* (Sarlegna and Sainburg, 2007; wrist data were filtered with a forward and reverse pass of a third-order Butterworth filter with a cutoff frequency of 10 Hz; only minima below 8% of the peak velocity were considered). We will refer to these methods as the *thumb*, *aperture* and *wrist* methods. We evaluated the results of the segmentation by plotting the sagittal position of the thumb and the grip aperture at the time point at which the movements were segmented (Fig. 2). As there were three rows in the target stimulus array (see Fig. 1), one would expect all the movements to be segmented when the sagittal position of the thumb was near one of these three rows. As the target was a 4.5-cm sphere, the expected grip aperture is about 4.5 cm. The distributions of trial-by-trial differences between the three conventional methods are plotted in Fig. 3.

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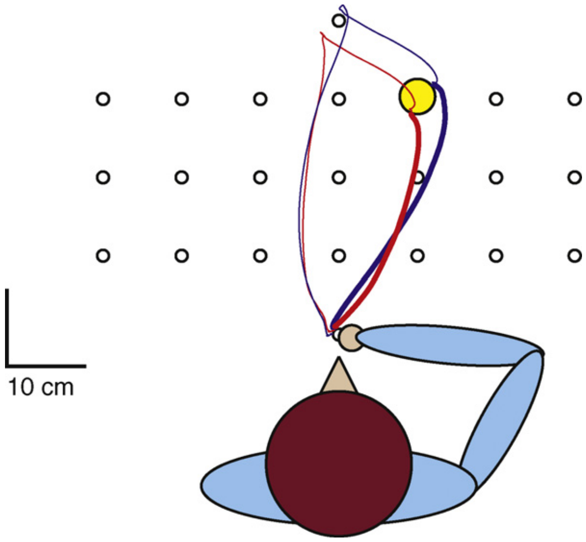

Fig. 1. Top view of the experiment used to illustrate the method: subjects were asked to move their hand from the starting position (either near or far) to pick up a sphere (indicated in yellow), put it in the place position (far or near respectively), and then bring their hand back to the starting position. The movement path of the thumb is shown in red and the path of the index finger in blue. The thicker lines represent the initial reach-to-grasp segment.

The large differences in Fig. 3 are caused by rather small differences in the execution of the movements on different trials. On some trials, conventional methods may even give a moment that is clearly incorrect (see Fig. 2). This occurs, for instance, if a subject unexpectedly closes the hand before the object is reached (Fig. 4a). An algorithm searching for the moment the aperture stops decreasing will call that the end of the movement segment, although it is clearly not the end if one considers the position of the hand (not shown). Relying on the minimum in the velocity profile of the wrist or the thumb velocity threshold can also lead to wrong conclusions. For instance, if the velocity remains above threshold until just before the subject places the sphere at the place position, segmentation occurred too late in the movement (see Fig. 2). After visual inspection of the aperture profile in Fig. 4a, the movement would be segmented when the aperture is first stable. The proposed Multiple Sources of Information method (MSI-method) segments the data near this moment for based on criteria that will be explained later. Fig. 4b shows that even when the algorithms work as intended, different segmentation methods give different results.

The above-mentioned examples illustrate four more things. Firstly, that the intuition we have about what to consider the end of a segment is not based on one, but on multiple aspects of the movement. A correct aperture alone is not enough; the hand should also be near the target and its speed should be low in order to consider that time point to be the endpoint. Secondly, relying on thresholds to segment data can be problematic if on some trials the thresholds are not reached. Thirdly, simply averaging the time points indicated by the various sources of information will not always yield a good estimate because averaging the very improbable time point found with the grip aperture information and the two improbable time points found with speed information (for the trial in Fig. 4a) will result in an extremely improbable time point between the three. Finally, the example illustrates that it is much clearer when a movement segment definitely does not end than when it does.

2. Methods

In the proposed Multiple Sources of Information method (MSI-method) the four insights mentioned in the last paragraph of the introduction are taken into account. To find the best possible time point at which to segment the movement, a researcher can consider as many sources of information as he wishes. Each source of information i that he wants to consider has to be transformed into an objective function F_i with values between zero and one. All the individual objective functions are multiplied to obtain a combined objective function F_{total} (Eq. (1)). The location of the maximum of this function will be will be regarded as the segment endpoint.

$$F_{total} = \prod_{i} F_i \tag{1}$$

The traditional way of finding a movement endpoint is essentially finding the maximum of an objective function F_{total} based on one source of information. For instance, to use the fact that subjects move slowly at the end of the movement segment, the objective function could be based on the tangential velocity of the wrist. As we want to have the objective functions to have a high value when it might indicate the end of a segment, we construct an objective function F_v that is high when the velocity at a moment is low

Table 1
Examples of the wide variety of criteria for segmenting reach-to-grasp movements. Segmentation is based on some property (How) of some variable, applied to some relevant structure (What).

Study	What					Variable					How
	Hand/ wrist	Index finger	Thumb	Object	Grip aperture	Displacement	Speed/ velocity	Position	Force	Size	
Biegstraaten et al. (2007)		√					√				Minimum
Bingham et al. (2008)		√					√				<5 cm/s
Chieffi et al. (1992)	√					√					<0.4 mm/frame
Cuijpers et al. (2004)	√						√				Minimum
Dijkerman et al. (2008)			√				√				<5 cm/s
Dubrowski et al. (2002)					√		√				<5 mm/s
Franz et al. (2008)		√	√	√				√			<3 mm
Franz et al. (2005)				√		√					>0
Grol et al. (2007)				√		√					>0
Hanisch et al. (2001)	√							√			Max
Mason and Carnahan (1999)		√	√						√		>0
Palluel-Germain et al. (2006)					√					√	Minimum
Paulignan et al. (1997)					√					√	Minimum
Roby-Brami et al. (2000)	√						√				Minimum
Sarlegna and Sainburg (2007)	√						√				Minimum[a]
van de Kamp and Zaal (2007)		√	√				√				<1 cm/s
Whitwell et al. (2008)					√		√				<2 cm/s

[a] Only minima below 8% of the peak velocity were considered.

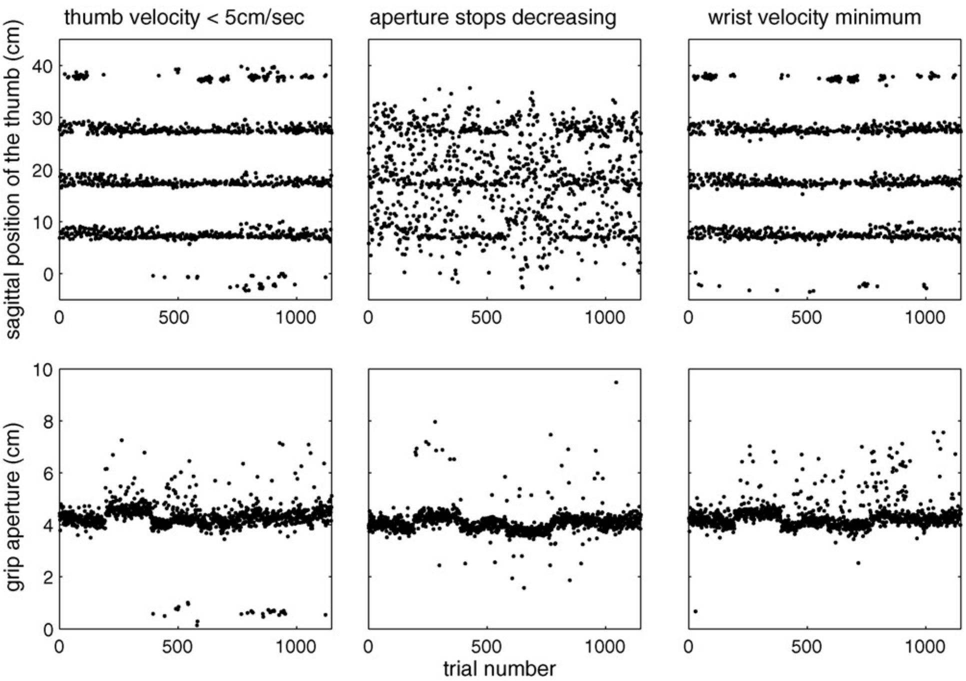

Fig. 2. Sagittal position of the thumb and grip aperture at the moment of the grasp obtained using different segmentation methods. The horizontal axes indicate consecutive trials (1148 in total performed by six different subjects).

(for instance; Eq. (6)). In that case, the maximum in the function would be considered the most likely candidate for the end of the movement segment.

This idea can easily be extended to more than one source of information. We might also want to consider that the subject's fingers must be near the target at the end of the movement segment. To select such a region around the target, the objective function F_p could have a value of one when the subject's fingers were nearer to the target than some distance threshold and zero when they were not. Multiplying the above-mentioned objective functions for the velocity F_v and the position F_p would result in a combined objective function F_{total} that reflects both objectives set by the researcher.

Because F_p is binary (i.e. it can only be zero or one) and will be multiplied with other objective functions, it will only eliminate some time points from consideration. This reflects the insight that it is much clearer when a movement segment definitely does not end than when it does. It is important to set boundaries leniently so as not to eliminate points that are possible based on the information sources at hand. For example, if we wanted

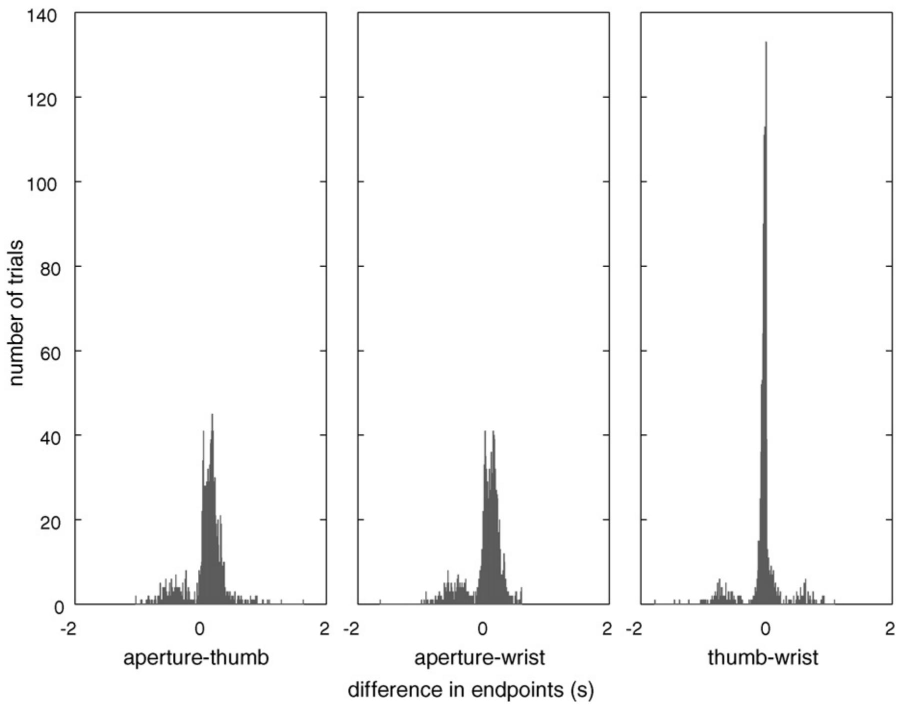

Fig. 3. Histogram of the difference in segmentation between the three conventional methods. The bin width is 10 ms.

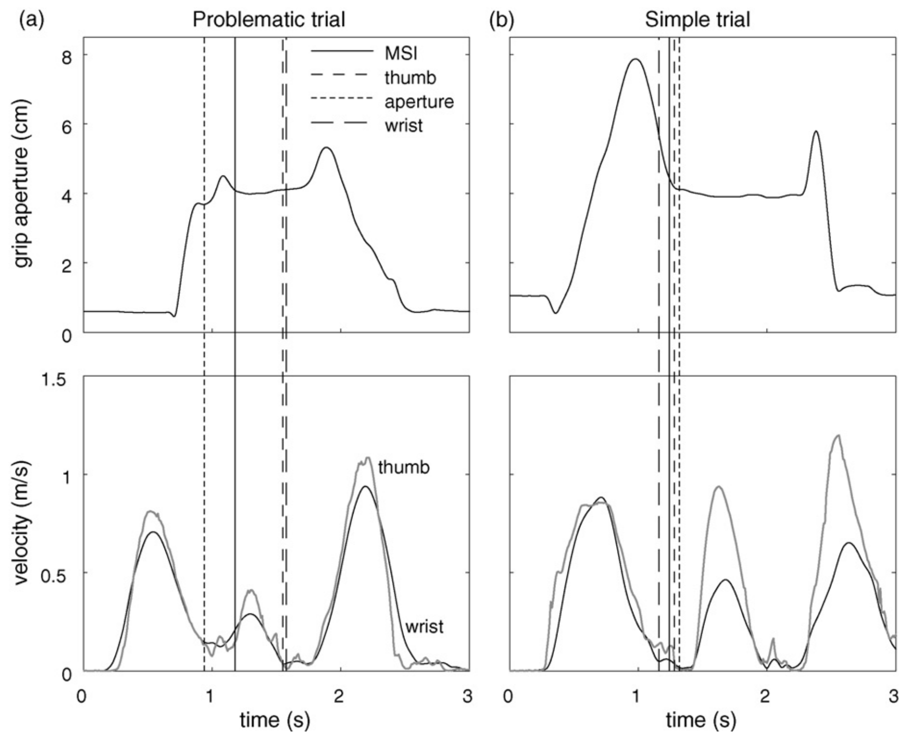

Fig. 4. Two example trials. In the trial depicted in panel (a) finding the first minimum in the aperture leads to a very different time point for movement segmentation than does a wrist velocity minimum or a thumb velocity threshold because the subject unexpectedly closed and reopened the hand before she reached the target. In the trial depicted in panel (b) the conventional algorithms work as intended, yet different moments for the segmentation are obtained by the different algorithms.

to include speed in a binary manner rather than the continuous manner described above, we need to be sure that our threshold is set at least as high as the highest velocity possible at the end of the movement segment. A high velocity threshold would lead to errors if it were the only source of information, but in combination with other sources it can just be used to eliminate time points that are extremely unlikely to be the end of the segment.

Whether one should choose a binary or a continuous objective function depends on the research question. If one wants to know at which speed people move when they grasp an object, it is very important not to let the speed influence the time point that is selected. In that case it is advisable to use a binary speed objective function with a high threshold so that a broad range of speeds is still considered possible. If one is not interested in the speed at which the object is grasped, but for instance in the hand orientation at the end of a reach-to-grasp movement, one can improve the sensitivity by using a continuous objective function for speed. The choice has to be made for each experiment, with the only restriction that there must be at least one continuous objective function in order to prevent multiple equivalent solutions.

If the maximum values of F_{total} does not result in segment endpoints that are meaningful to the researcher, either one of the objective functions is constructed incorrectly (for instance, objects are grasped while moving at a higher velocity than the set threshold) or a source of information that is meaningful to the researcher is not included and its objective function should be added. Following this procedure forces the researcher to explicitly state the sources of information used to obtain the segment endpoint. Applying the same objective functions to all trials in a dataset ensures objective segmentation of the movements.

In the example presented in the next section, we will demonstrate how to implement the MSI-method. In the subsequent section, using the same data that was used for Fig. 2, we will show that the method is quite robust with respect to some of the arbitrary choices that have to be made (as reflected in the weight attached to the different sources of information).

3. Example

We will now give an example of how one can construct objective functions to segment movement data using the MSI-method. The first step is to decide which parameters provide useful information. For our sphere-grasping example (Fig. 1), at the end of the segment the digits should be within the region within which the sphere could be, the speed of the wrist should be low, the distance between the thumb and the index finger should be close to the size of the sphere, and the gap between the thumb and index finger should be closing with a decreasing velocity. To formalize these constraints, we considered the average sagittal position and height of the thumb and index finger, the speed of the wrist, the distance between the index finger and the thumb (grip aperture), the change in grip aperture (grip velocity), and the rate at which this velocity changes (grip acceleration). The time-courses of these measures for one example trial are shown in Fig. 5. To be able to find the optimal time point for the end of the movement segment based on these sources of information, each individual source of information i was first transformed into an objective function F_i.

We will start by constructing binary objective functions to rule out some time points that can definitely not be the end of the segment. First, a time point cannot be the endpoint if the hand is not in the region in which spheres were positioned. A single sagittal position was obtained for each time point by averaging the coordinates of the thumb and the index finger. When this coordinate was outside the range of all possible locations of the sphere, the value of the objective function for this measure was set to zero. Otherwise, it was set to one (Fig. 6a). This is described by Eq. (2) where F_s is the objective function based on the sagittal position, s is sagittal position, and $s_{\min}$ and $s_{\max}$ are the borders of the relevant space (6 cm and 34 cm from the start point respectively; the sphere could

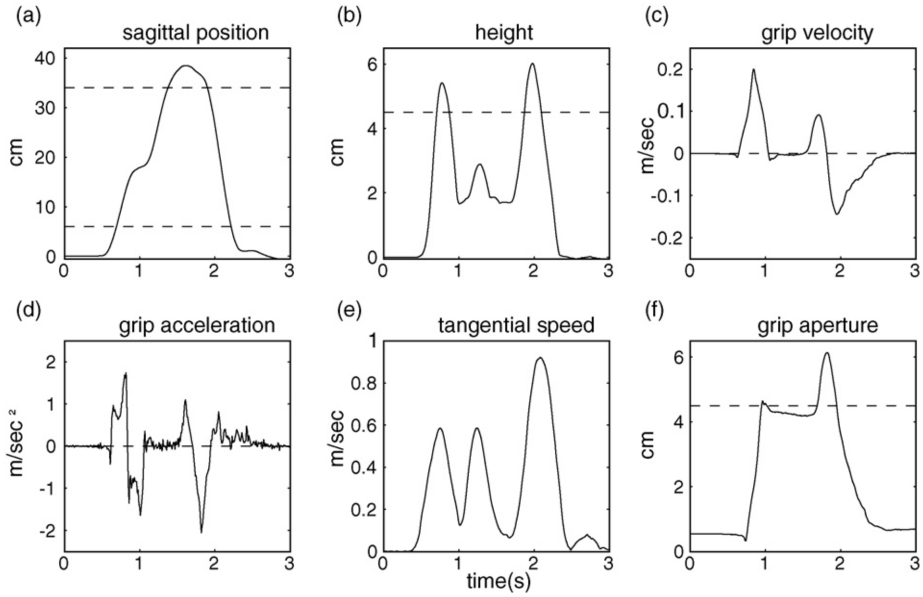

Fig. 5. Time profiles of the kinematic variables that we used to determine the end of one representative reach-to-grasp movement segment. Dashed lines represent values that play a special role when doing so; see text for further explanation.

be placed at 10, 20 and 30 cm).

$$F_s(s < s_{\min} \vee s > s_{\max}) = 0$$
$$F_s(s_{\min} \le s \le s_{\max}) = 1 \quad (2)$$

Allowing the end of the movement segment to occur anywhere that the sphere could be, only ensures that the end of the placing movement or of the return movement are not inadvertently considered to be the end of the grasping movement. We could also have adjusted the range for each trial to only consider points within a smaller region around the position of the sphere in that specific trial.

The average height of the thumb and index finger was obtained in the same manner as the sagittal position. The value of the objective function was set to zero when the average height was above the top of sphere, and to one when it was below the top of the sphere. The objective is to segment the movement when the subject's fingers grasp the sphere so they cannot both be above the top of the sphere (Fig. 6b). In Eq. (3), F_h is the objective function based on height, h the height from the surface, and d the diameter of the

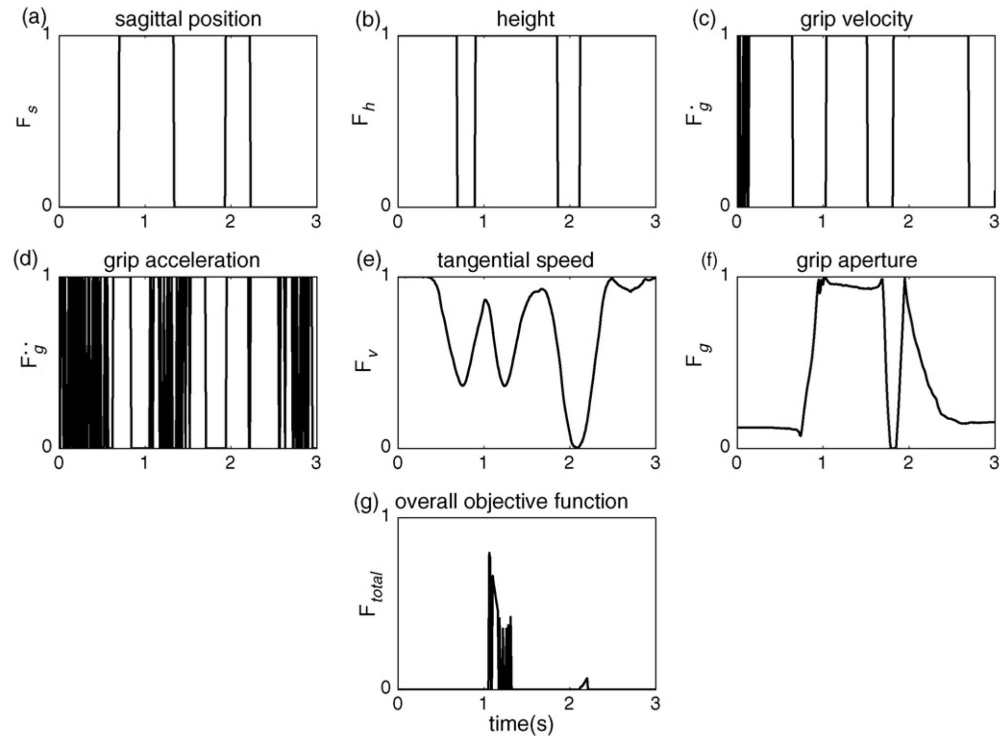

Fig. 6. (a–f) Objective functions for a time point being the end of the movement segment based on the kinematic profiles in Fig. 5. When the grip is not changing, grip velocity and acceleration fluctuate around zero causing the black blocks in panels *c* and *d*. (g) Multiplication of the objective functions in panel *a* through *f* results in a clear maximum in the overall objective function, which was taken to be the end of the movement segment.

sphere (4.5 cm).

$$F_h(h \leq d) = 1$$
$$F_h(h > d) = 0 \quad (3)$$

Of course we could have incorporated the intuition that subjects take into account the center of mass of the object to produce a stable grasp. In that case, we would have made it an objective to segment the movement when the average height of the thumb and index finger was half the height of the sphere. The values of the objective function could decrease in a continuous manner as the average height deviated from half the height of the sphere. Although this method definitely has some advantages over the one we chose to use, the disadvantage is that it includes an assumption about where the fingers will be positioned at the moment the subject grasps the sphere. As our research question was exactly that (Schot et al., 2008), the risk of introducing a bias through this assumption was not desirable for the present example.

The velocity and acceleration of the change in grip aperture can also be used to construct objective functions. The thumb and index finger should be coming closer together rather than moving further apart. In other words, grip aperture should be decreasing. This is reflected in the first derivative of grip aperture being negative rather than positive or zero (Fig. 6c, Eq. (4)). We therefore set the values of an objective function $F_{\dot{g}}$ to one when the first derivative of grip aperture $\dot{g}$ was negative. Otherwise it was set to zero.

$$F_{\dot{g}}(\dot{g} < 0) = 1$$
$$F_{\dot{g}}(\dot{g} \geq 0) = 0 \quad (4)$$

Moreover, the decreasing of the grip aperture should be decelerating rather then accelerating. This is reflected by a positive second derivative of aperture. The value of the objective function $F_{\ddot{g}}$ was set to one when the second derivative of grip aperture $\ddot{g}$ was larger than zero. Otherwise, it was set to zero (Fig. 6d, Eq. (5)).

$$F_{\ddot{g}}(\ddot{g} > 0) = 1$$
$$F_{\ddot{g}}(\ddot{g} \leq 0) = 0 \quad (5)$$

We have now ruled out all the time points that certainly cannot be the endpoint based on the objectives we formulated regarding sagittal position, height, grip velocity and grip acceleration. Next, we want to discriminate amongst the remaining time points in order to find the time point with the highest value of the combined objective function. That is, the time point that matches all the objectives taken together most closely. To do so we introduce two continuous objective functions.

The first is the speed of the wrist. We want to convert the speed into a continuous range of values between zero and one. People generally slow down their movement when they want to grasp something, so the value of the objective function should be higher when the speed of the wrist is low. As the hand does not have to stop, there is no clear distinction between possible and impossible speeds. We divided all the measured values by the maximum speed to obtain values between 0 and 1, and then subtracted the resulting values from 1 so that the lowest speed was assigned the highest value (Fig. 6e):

$$F_v = 1 - \frac{v}{v_{\max}} \quad (6)$$

In Eq. (6), F_v is an objective function taking only velocity into account, v is velocity at that moment, and $v_{\max}$ is the maximum velocity on that trial. Many other equations are possible. We will return to this issue when discussing how robust this method is.

The final source of information that we included in our combined objective function was aperture. The sphere used in this experiment had a diameter d of 4.5 cm. Therefore, the objective is to segment the movement when the distance between the thumb and the index finger was close to d. We determined the extent to which the grip aperture g deviated from d. If the sphere was grasped firmly or not exactly through the center of mass, g can be slightly smaller than d. Time points at which g was larger than d are very unlikely to have been the end of the grasping movement, but might occur if subjects grasp with another part of the digit than the part considered to be the 'position' of the digit by the researcher. Therefore, we wanted grip apertures near d to have the highest values and grip apertures that were a certain amount smaller than d to have a higher value than grip apertures that were the same amount larger than d. To achieve this we multiplied the above-mentioned differences $|d-g|$ by three when g was larger than d. The multiplication factor three is arbitrary. It reflects one's confidence in the above reasoning about viable grip apertures. To construct an objective function with values between zero and one, we divided $|d-g|$ by d and subtracted the outcome from 1. Values below zero were set to zero (Fig. 6f). This procedure is summarized in Eq. (7) where F_g is the objective function taking only grip aperture into account, g is grip aperture, and d is the diameter of the sphere.

$$F_g(g < d) = 1 - \frac{d-g}{d} = \frac{g}{d}$$
$$F_g\left(d \leq g \leq \frac{4}{3}d\right) = 1 - 3\frac{(g-d)}{d} = \frac{4d-3g}{d} \quad (7)$$
$$F_g\left(g > \frac{4}{3}d\right) = 0$$

Each time point in a trial now has six values between zero and one, reflecting the objectives based on each of the six different sources of information. Multiplying these values gives the overall objective function F_{total} (Fig. 6g, Eq. (8)). The time point with the maximum value of this overall objective function is considered to be most likely to be the end of the grasping movement.

$$F_{total} = F_s \cdot F_h \cdot F_{\dot{g}} \cdot F_{\ddot{g}} \cdot F_v \cdot F_g \quad (8)$$

4. Robustness of the MSI-method

To give an indication of how robust the method is against arbitrary choices made by the researcher, we ran the procedure seven times. We ran it once with all the sources of information included as described above. The other six times we let one of the sources of information contribute less strongly to the combined estimate of the endpoint. Instead of letting the values vary between zero and one, we let it vary between 0.5 and 1. Thus one of the objective functions described above (F_i) was replaced by F_i' (Eq. (9)).

$$F_i' = 0.5 + 0.5 \cdot F_i \quad (9)$$

One consequence of changing an objective function in this manner is that no time point can be excluded on the basis of this source of information alone. The influence of reducing the contribution of one source of information can be seen in Fig. 7. Note that for our data the method is completely robust against decreasing the contribution of the sources of information that were transformed into binary objective functions. Thus points that were clearly not the endpoint are still rejected based on other objectives. Continuous objective functions determine the precise time point where the movement is segmented, so decreasing the contribution of a source of information with a continuous objective function does lead to changes in the precise end point. However these changes are considerably smaller than the difference between endpoints found by single criterion methods (compare Figs. 3 and 7; Note the difference between the timescales).Comparison of the MSI-method with conventional methods

Since redundancy is not a problem for the MSI-method, the researcher can combine many objective functions and can even add objective functions if it turns out that the segmentation is not

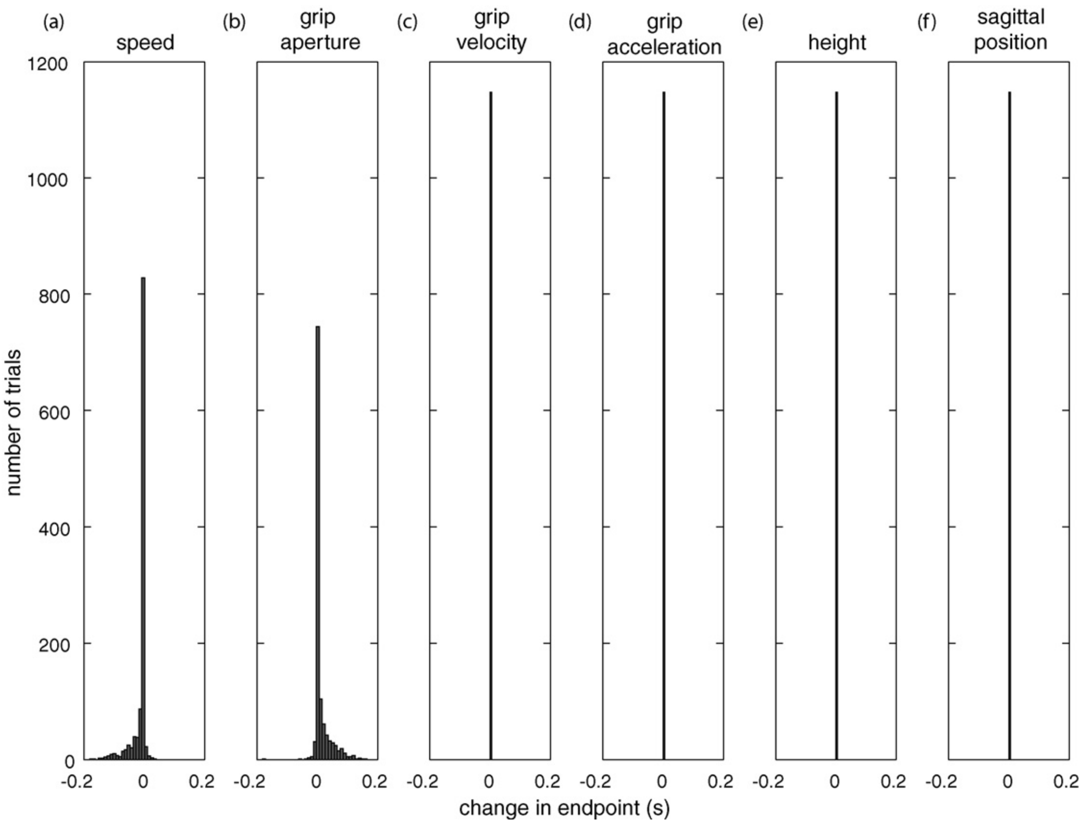

Fig. 7. Robustness of the MSI-method. Change in the timing of the ends of the movement segments when the contribution of one of the sources of information (indicated at the top of the panel) to the overall objective function is reduced (see text for details). For three trials (one in panel a and two in panel b), the absolute difference exceeded 200 ms, so these trials are not visible in the graphs. Note the difference between the timescales with Fig. 3.

meaningful for all trials. These objective functions are applied to all the trials in a dataset, so no biases can be introduced through adjustments of single trials on the basis of visual inspection. Consequently, the results of the MSI-method are more objective than the conventional methods. If the objective functions are chosen well, the MSI-method also cannot come up with meaningless values.

To verify this, we plotted the sagittal position of the thumb and the grip aperture at the endpoints of the grasping segment according to the MSI-method, as we did in Fig. 2 some conventional methods (Fig. 8). We obtained values that can be expected based on the constraints of the task for the sagittal position of the thumb as well as for grip aperture. This demonstrates that combining several sources of information can be combined to obtain endpoints that are more meaningful than methods using just one or two. Some methods used in the literature can be viewed as a simple implementation of the MSI-method. For instance, the method used by Sarlegna and Sainburg (2007) only considered minima below 8% of the peak velocity. This corresponds to combining a continuous objective function with a binary one, but in this case both based on wrist velocity.

5. Discussion

The benefit of the MSI-method over a method that only uses one criterion is that if one criterion leads to a wrong conclusion about which time point should be regarded as the end of a segment, other criteria can rule out this time point as a possible endpoint. If, for example, a subject holds his or her hand still above an object before grasping it, this would be detected as the end of the segment if only a speed criterion were implemented. However, with the MSI-method, the value of the overall objective function at this time point would presumably be very low due to the large grip aperture, or zero due to the height being above threshold. The essence of the MSI-method is not to define new, more general criteria, but to implement conventional criteria that would normally underlie post-hoc adjustments based on visual inspection. If a researcher adds objective functions for all the criteria that underlie post-hoc adjustments, the results obtained will be more meaningful than those obtained by methods using fewer criteria. The fact that the criteria are applied to all the trials makes the method objective.

We have shown that the segment endpoints obtained using the MSI-method are meaningful in the sense that we found very little variation in grip aperture and three values for the sagittal position of the thumb (Fig. 8), as one would expect for grasping spheres at three distances. When using at the other methods, there are some obvious errors (Fig. 2). Evidently, the velocity threshold of 5 cm/s for the thumb, or of 8% of the maximum velocity for the wrist was too low on some trials. The thresholds were only reached when subjects placed the sphere in the place position or even when they moved their hand back to the starting position to start the next trial (evident from the near zero apertures on these trials). Increasing the threshold would probably solve this problem, but trials that are segmented correctly would then be segmented earlier in the movement resulting in less accurate grip apertures because the fingers are still further apart. A disadvantage of thresholds in general is that they can only be used successfully if the data is very consistent over trials. In the present example, and probably in the majority of datasets, speeds were quite variable at the time subjects grasped the sphere, so any value that would be chosen as a threshold would lead to errors in a number of trials.

Both the wrist velocity minimum criterion and the thumb velocity threshold criterion also segmented trials at time points where

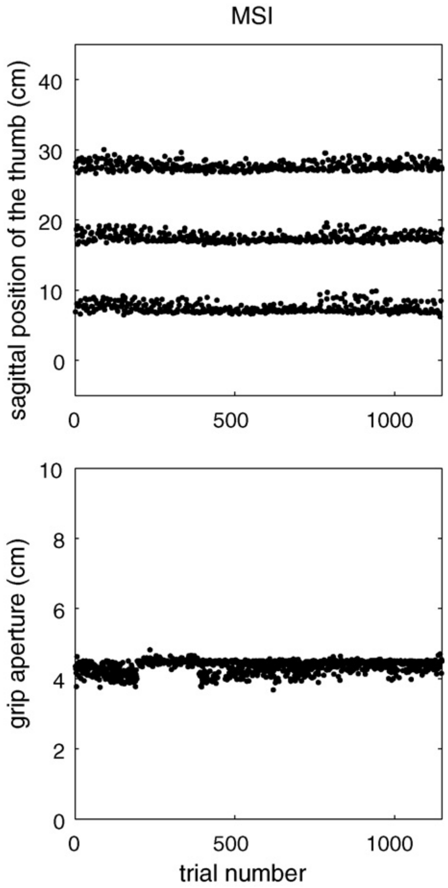

Fig. 8. Sagittal position of the thumb and grip aperture at the end of the segment as obtained using the MSI-method. See legend of Fig. 2 for further details.

the aperture was too large, presumably because the fingers are sometimes still closing after the wrist stops moving and because the thumb sometimes stops moving before the index finger stops moving.

The aperture often only stops decreasing when the subject is already transporting the sphere to the place position. This is the result of the fact that subjects squeeze the object as they lift it because holding a moving object requires more force than holding a stationary one (Flanagan and Wing, 1993). Therefore, the point at which aperture stops decreasing is quite late (see Fig. 5f for an extreme example). This results in quite plausible grip apertures, but the sagittal position of the thumb can be clearly incorrect (see Fig. 2, middle panel). Detecting the first minimum in noisy, unfiltered data is less likely to segment movements long after contact, but it is more likely to segment the movement too early, resulting in grip apertures that are too large. This illustrates that the extent to which the data is filtered has profound effects on the segmentation when it relies on the detection of local minima. The MSI-method has the advantage that no local extrema have to be detected, so filtering of the data will not greatly influence the segmentation.

We would like to stress once more that the criteria chosen here and formalized in Eqs. (2)–(7) are not in any way meant to be the best ones in all situations. Which parameters can be used and how they are best transformed into objective functions depends on the experimental set-up and the research question. For example, we did not measure contact force, but it could be taken into account by for instance assigning a value of zero whenever there was no contact or contact force was decreasing and a value of one in all other cases. More complicated procedures including Kalman filters (Sauter et al., 1991) or linked double window techniques (Marple-Horvat et al., 1996) can also be used to construct objective functions.

The nature of the stimuli also makes some objective functions preferable over others. For example, if the objects that are to be picked up are not circular (e.g. Cuijpers et al., 2004), the aperture at the end of the movement depends on the grip orientation and will vary between trials. Choosing a continuous objective function for aperture could therefore lead to a bias, because the correct aperture depends on the orientation of the grip. In that case, it might be preferable to construct a binary objective function that assigns the same value of the objective function for a range of apertures. Conversely, if movement time is the main factor of interest, rather than the grasping points, one can be much more selective about the positions of the digits. The MSI-method is not limited to this specific combination of measures, but is the idea that combining measures in terms of roughly estimated objective functions can lead to robust judgments of the ends of movement segments. Also, its application is not limited to prehension tasks but can be applied to a wide variety of movements, such as eye movements or cyclical lower limb motion.

In conclusion, we state that a real movement endpoint cannot be found because it does not exist as such. The intuition about the end of a movement segment is based on multiple criteria that should be combined to find the best possible time point to call the endpoint. This is a formalization of what people do when they correct endpoints after visual inspection. We have shown that combining the objective functions constructed from multiple sources of information gives reliable endpoints that are not very sensitive to the precise setting of each objective function.

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