An algorithm separating saccadic from nonsaccadic eye movements automatically by use of the acceleration signal

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Summary

An algorithm is described to discriminate automatically between saccades and slow eye movements. Sampled data of the eye position have been used to calculate the momentary acceleration of the eye. The higher acceleration values of the saccadic eye movements as opposed to the slow compensatory or pursuit eye movements served to differentiate between the two. The method is demonstrated by search-coil data in squirrel monkeys.

Introduction

Vestibular or optokinetic nystagmus is a sequence of compensatory "slow" reflex eye movements and rapid backward movements (saccades). The saccades reset the eye near its initial position. To achieve the response function of the pursuit movement of the OKN system with respect to a given moving stimulus, the backward saccades have to be rejected from the analysis. In the past numerous attempts have been made to separate the two components of eye movements automatically. In most of the algorithms developed the eye angular velocity signal V_e was used. For example, Wall and Black (1981) detected successive extreme eye positions and calculated V_e in between. Barnes (1982) introduced convenient V_e thresholds; Inchingolo and Spanio (1985) searched for the peak velocity and defined the beginning and end of a saccade a few data points before or after the peak. Because the V_e ranges of the quickest slow eye movements and the slowest parts in the saccades overlap, V_e is not a good signal for distinguishing the two components of eye movements. All the methods described required at least the interaction of an operator to use the high pattern discrimination ability of the human visual system. Recently Arzi and Magnin (1989) described an automatic algorithm to overcome the disadvantages mentioned. The authors introduced a membership function of unity (1) for slow and zero (0) for saccadic eye movements. To achieve this membership function *a priori* information is necessary. This information was obtained from the global pattern of the velocity response. In an iterative procedure the maximal discrimination had to be calculated. This method is useful for regular responses of the eye movement system, for example sinusoidal V_e responses to vestibular stimulation, but it does not work when the response is unpredictable, as in optokinetic afternystagmus OKAN, for example, with its altering and unforeseeable time course.

Since the change in V_e at the beginning and end of the saccades, which are ballistic movements, is faster than with slow eye movements, we tried to use the different ranges in acceleration for discrimination.

Method

Acceleration signal processing

The acceleration signal was produced from sampled eye position data stored on file by lowpass filtering and calculating the second derivative. For lowpass filtering finite impulse response (FIR) filters were used (Rabiner & Gold, 1975). FIR filters with a linear phase have symmetrical coefficients which can be written as :

$$h(0) = 2 \cdot f_c / f_s, \qquad h(M) = h(-M) = [\sin(h(0) \cdot \pi \cdot M] / (\pi \cdot M),$$

where f_c and f_s represent the lowpass cutoff frequency and sample frequency respectively; M is an integer. To diminish the effects of the finite number of coefficients a Hamming window was used. To maintain the low-pass filtered data the position data were convolved with the normalized $N = 2M + 1$ filter coefficients thus achieved.

The second derivative was obtained by convolution of the filtered signal with the kernel { 1, -2, 1 } divided by the square of the sample interval representing the repeated differentiation of a 2-point first-derivative approximation.

Because of the linearity of these operations filtering and differentiation can be combined and result in a convolution kernel of $N + 2$ coefficients for calculation of the filtered second derivative.

When cutoff and sample frequency have been selected, the properties of the filter are determined by the number of coefficients. With increasing M, the frequency response is steeper around the cutoff frequency but the step response exhibits more overshoot. Because the filtered second derivative is only used for the detection of saccades of different amplitudes, the FIR filter has to be optimized with respect to the step response overshoot. For a small but tolerable step response overshoot, the integer M could be well approximated by $M = INT(0.7 \cdot f_s / f_c)$. Depending on the quality of the eye position data, the lowpass cutoff frequency f_c has to be determined (with a selected sample frequency f_s) so that a sufficient signal-noise ratio in the filtered second derivative for detection of saccades is obtained, as demonstrated in Fig. 1 (trace 3) for the absolute value of acceleration. This signal to noise ratio is given by the noise of the position signal itself but depends in addition on different factors such as the kind of signal prefiltering, resolution of the analog-digital conversion and the sample frequency. Once the best cutoff frequency is determined for the eye movement recording method used, FIR filter coefficients using the given approximation for M can be calculated for different sample frequencies. Applying the electromagnetic scleral search-coil technique (Robinson, 1963) for measuring eye position, as in the data demonstrated, a cutoff frequency of 25 cycles $\cdot$ s^{-1} was found to be convenient. Sample frequency was 250 samples $\cdot$ s^{-1}. Comparable results with respect to the signal to noise ratio of $|A_e|$ were achieved using sample frequencies between 166.7 and 1000 samples $\cdot$ s^{-1}.

Saccade detection algorism

The algorithm using A_e values for discrimination of the two components of eye movements will be explained on the basis of Fig. 1. As an example we used a section of an eye movement registration which includes a saccade superimposed by a small second one (arrow in trace 1). Traces 2 and 3 show the velocity and the absolute value of acceleration respectively. The parameters used were f_s = 250 samples $\cdot$ s^{-1}, f_c = 25 cycles $\cdot$ s^{-1}, M = 7. To become independent of the direction of the saccade and avoid zero crossings, we used the absolute value of acceleration $|A_e|$.
In this kind of representation the saccadic eye movements normally show a two-peak time course; the first saccade, which is superimposed by the small one, exhibits a four-peak positive time course.

The beginning of a saccade is determined by the first traverse of a given acceleration threshold (dashed line in trace 3) when the absolute values of acceleration $|A_e|$ in a succeeding time interval ΔT_1 - corresponding to $K_1 = \mathrm{INT}\ (\Delta T_1 \cdot f_s)$ samples - are overthreshold. In all data presented, ΔT_1 = 12 ms, corresponding to K_1 = 3 in this example. With respect to the filtering used we found good values for the threshold between 800 and 1000 degrees $\cdot$ s^{-2}. Thus normal and small saccades can be detected reliably. Because of the fact that $|A_e|$ within a single saccade can fall below the threshold, a criterion had to be defined whether this indicates the onset of a succeeding slow component or not. Accordingly, after such a traverse below the threshold, we tested $|A_e|$ in a time interval ΔT_2 - corresponding to $K_2 = \mathrm{INT}\ (\Delta T_2 \cdot f_s)$ samples. If $|A_e|$ is subthreshold for all K_2 samples, they belong to the slow component of the eye movement and the fall below the threshold was the end of a saccade. For all samples which are subthreshold, the membership function is set at unity (1). When the acceleration crosses the threshold before K_2 subthreshold samples are detected, the acceleration values belong to a saccade and the membership function is set at zero (trace 4). A ΔT_2 of 16 ms was chosen corresponding to K_2 = 4 samples. The time window ΔT_2 represents a refractory period.

The membership function was stored on file. Slow components of position or velocity for example can be achieved by comparing this data and the membership function at unity. When the latter is zero, position or velocity data were not discarded but set at a never occurring value. Thus a confusing data reduction can be avoided. If the saccadic components are the point of interest, the comparison has to be carried out in the other way. Slow-phase components of traces 1 and 2 are shown in traces 5 and 6 respectively.

If we define the membership function on the basis of threshold crossing, a saccade represented by zero in this function can be over- or underestimated in its duration, as mentioned above. When interest is only directed to detecting saccades in eye movement recordings, the membership function so defined works well. If saccades are to be rejected, it could be necessary to spread the saccade in its representation in the membership function because of the asymmetry in the rise and fall of a saccade in the acceleration time course. For this we used additional time windows ΔT_3 and ΔT_4 before and after $|A_e|$ crossed the threshold at the beginning and end of a saccade respectively. With respect to the sample frequency, these time windows can be represented analogously to K_1 and K_2 by numbers of samples K_3 and K_4. For these samples the membership function is also set at zero.

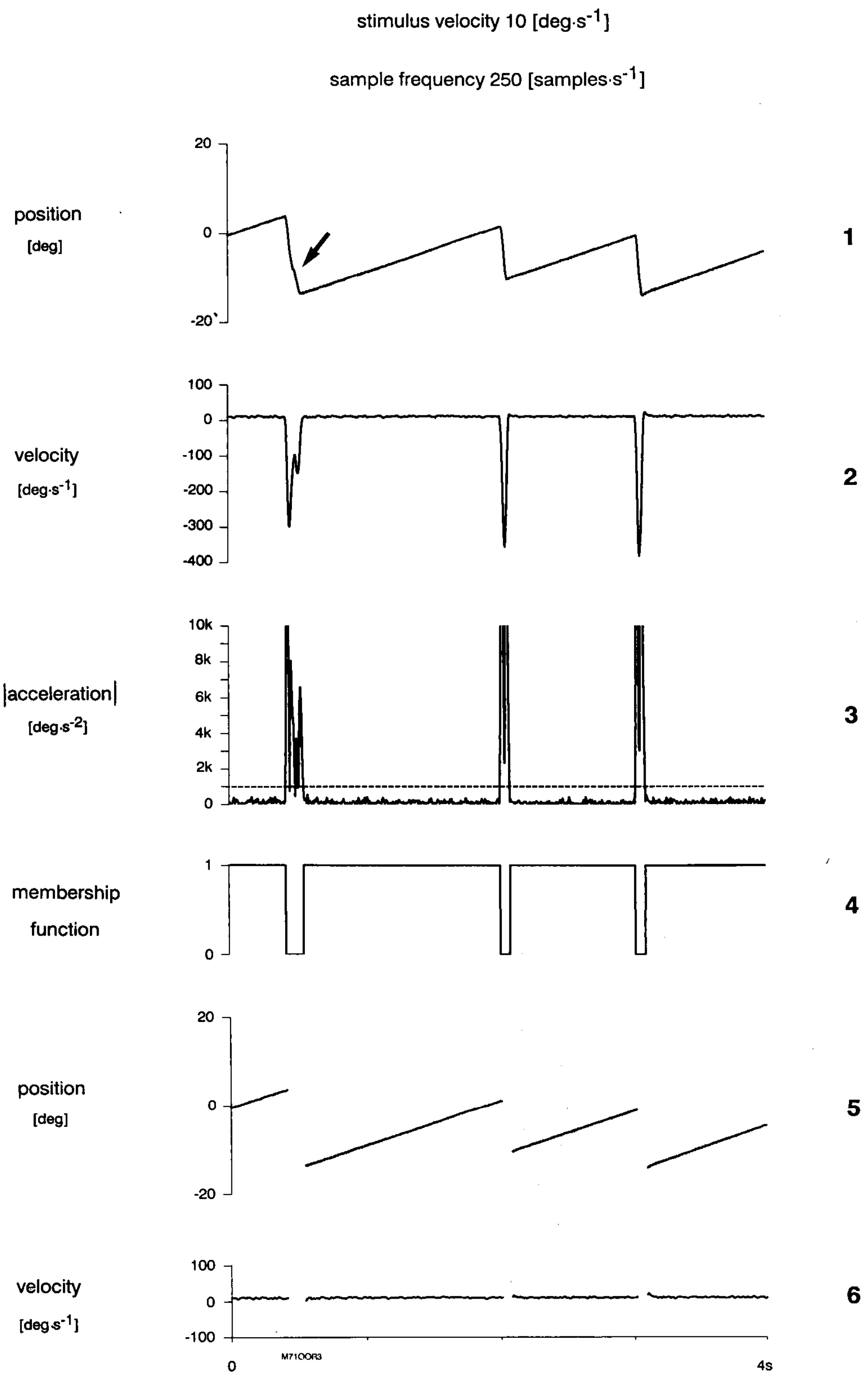

Fig. 1: A section of an OKN registration example to explain the operation of the saccade detection algorithm. Data were measured in a squirrel monkey (Saimiri sciureus) by means of the electromagnetic search coil technique. Trace 1 shows the eye position signal. Sample frequency f_s = 250 samples · s^{-1}. The first saccade is superimposed by a small one. In traces 2 and 3 the velocity V_e and absolute value of acceleration $|A_e|$ are plotted respectively, lowpass cutoff frequency f_c = 25 cycles · s^{-1}, M = 7. Trace 3 shows the selected threshold of 1000 deg · s^{-2}. In trace 4 the membership function defined by the transitions through the threshold is plotted. Using this function the slow-phase position and velocity from traces 1 and 2 are plotted in traces 4 and 5 respectively.

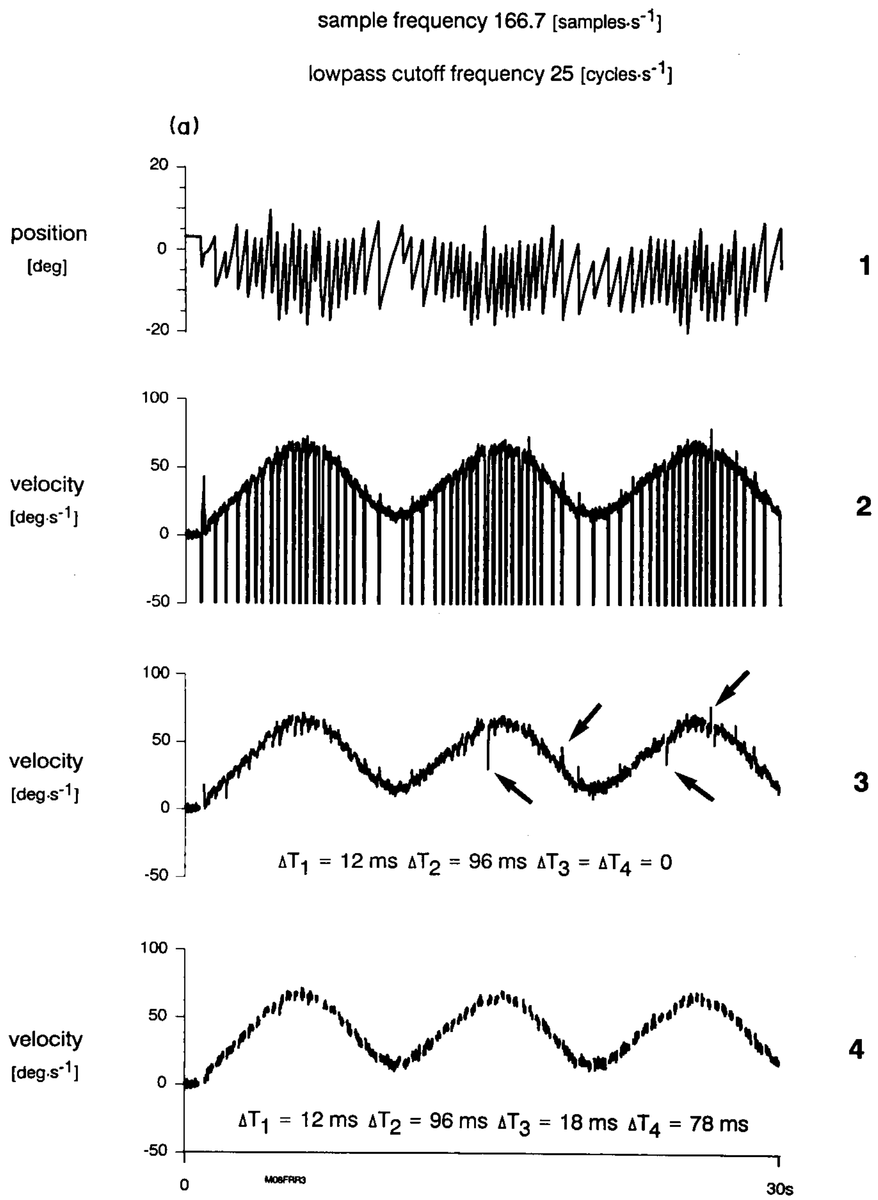

Fig. 2 (a): Sinusoidally modulated stimulus function; horizontally moving stripe pattern of 15 degrees period. Traces 1 and 2 show the eye position and velocity respectively. Sample frequency f_s = 166.7 samples·s^{-1}, lowpass cutoff frequency f_c = 25 cycles·s^{-1}, M = 5. In trace 3 the slow-phase velocity is plotted using a membership function defined by the traverses through the acceleration threshold. The last parts of particularly asymmetric saccades are visible (arrows). Using time windows ΔT_3 = 18 ms and ΔT_4 = 78 ms, the membership function is optimized with respect to suppression of saccadic components. The remaining slow-phase component of the eye movement is seen in trace 4.

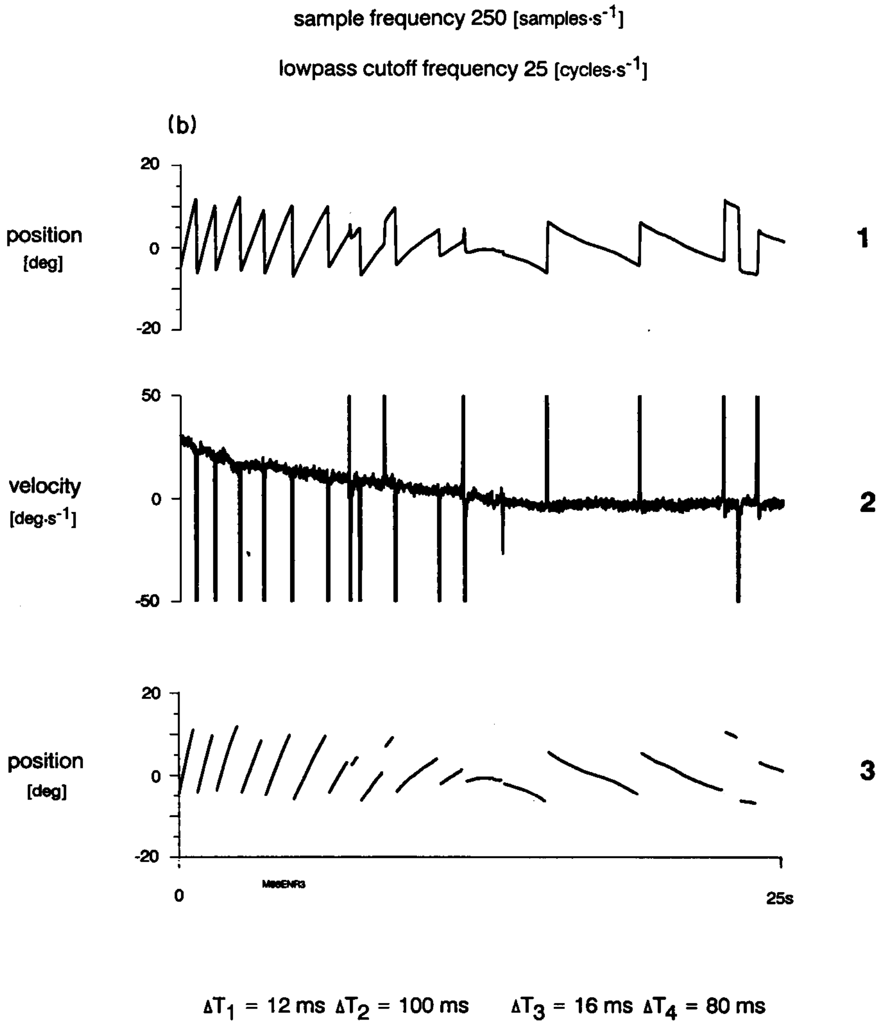

Fig. 2(b): After horizontal optokinetic stimulation stopped, OKAN is determined exclusively by the time course of the internally stored velocity signals. The transition from OKAN I to OKAN II is selected as an example. Sample frequency f_s = 250 samples · s^{-1}, lowpass cutoff frequency f_c = 25 cycles · s^{-1}, M = 7, time windows ΔT_3 = 16 ms and ΔT_4 = 80 ms. Using the described algorithm the slow-phase eye position is plotted in trace 3.

Results

Applications of the method described are demonstrated for a different types of stimulus responses in Fig 2. In Fig. 2a optokinetic nystagmus during sinusoidal modulation of the stimulus velocity around 46 deg · s^{-1} is shown. Sample frequency f_s = 166.7 samples · s^{-1}, lowpass cutoff frequency f_c = 25 cycles · s^{-1}, M = 5. In trace 3 the slow-phase velocity using a membership function defined by the transitions through the absolute acceleration threshold of 1000 deg · s^{-2} is plotted. The last parts of the saccades can be seen (arrows). Spreading the saccades in their representation in the membership function by ΔT_3 = 18 ms and ΔT_4 = 78 ms, corresponding to K_3 = 3 and K_4 = 13 samples before and after the saccade crosses the threshold, results in an optimized membership function for saccade rejection. The application of this optimized function is seen in trace 4.

In Fig. 2b eye movements in the dark after optokinetic stimulation as a result of the internally stored velocity value are seen. The example shows the transition from OKAN I to OKAN II in which the slow-phase velocity is low and small saccades occur. Sample frequency f_s = 250 samples · s^{-1}, lowpass cutoff frequency f_c = 25 cycles · s^{-1}, M = 7. In trace 3 the slow component of the eye position is plotted. Time windows were chosen at ΔT_3 = 16 ms and ΔT_4 = 80 ms, corresponding to K_3 = 4 and K_4 = 20 samples before and after the saccade crosses the threshold. All registrations are measured by means of the electromagnetic search coil technique in Squirrel monkeys.

Discussion

If the objective is only to reject saccades from eye movement recordings, the algorithm described has been found to be useful. To achieve the components of slow-phase eye movements, the choice of the parameters ΔT_3 and ΔT_4 can be made more generously, especially when the data during the saccades have to be interpolated by a least squares polynomial approximation. A good choice for the time windows is $\Delta T_3 \sim$ 10 ms, ΔT_4 < 100 ms.

Investigations of the saccadic components on the other hand have to take into account the misjudgement of a saccade in its representation in the membership function. To determine the beginning and the end of saccades exactly, we used the membership function defined by threshold crossings to *detect* the saccades and searched after spreading this function by ΔT_3 and ΔT_4 for the maximum and minimum of the eye position signal while the thus manipulated membership function is zero. As a result, the amplitude and duration of each saccade can be determined as well as the amplitude of the slow eye movements in OKN to calculate the cumulative eye position, for example. Searching for the maximum value of the eye velocity signal while the membership function is zero one achieves the peak saccade velocity values. This offers the possibility to define the beginning and end of each saccade in another way, namely by the values at which the velocity crosses a threshold of, for example, 10% of the peak saccade velocity.

An advantage of the described algorithm is that after exploring the suitable cutoff frequency of lowpass filtering and choosing the time windows ΔT_1 to ΔT_4 for a special eye position recording method, large amounts of data can be handled automatically with the chosen parameters.

Saccade detection was demonstrated with experimental data in which only the eye position data were recorded. When eye velocity achieved by means of appropriate analog filtering is available, the method can be easily adapted.

The algorithm was demonstrated on stored sampled eye position data as an off-line procedure. Using hardware digital signal processors, lowpass FIR filtering and calculation of derivatives could be calculated during sample intervals. Thus a real-time processing of eye recordings becomes possible. In a next step this will be attempted in order to display eye movement components or neuronal activity with respect to the onset of saccades for example in real time.

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