Computerized procedure for analyzing hand kinematics with a peg-moving task (Sarah-Pegworks)

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This article describes Sarah-Pegworks, a computerized procedure for analyzing hand kinematics based on the peg-moving task. The procedure, developed in Visual Basic 6 programming language, includes (1) processing raw data from an infrared motion-tracking system, (2) identifying movement components, and (3) analyzing and presenting hand kinematic information in numerical and graphic outputs. Fifty-five normal adults set the parameters relative to filtering and movement identification. A case was presented to illustrate the clinical value of this procedure.

Three-dimensional (3-D) movement analysis techniques allow the investigation of details of a manual task by decoding movement into several components (Jeannerod, Paulignan, & Weiss, 1998). Through a motion analysis system, the researcher or clinician is able to quantify and evaluate upper limb movement disorders and the effects of treatment. However, these methods have not been widely used, due to a lack of standardized procedures and tools for processing and analyzing the huge amount of data generated by this technique (Veeger, Yu, An, & Rozendal, 1997).

Rau, Disselhorst-Klug, and Schmidt (2000) compared upper limb analysis with gait analysis and addressed a number of issues resulting from the interchange of these methodologies. According to these authors, upper extremity movements differ from gait because they are task dependent, noncyclic, and necessarily 3-D; their external forces are difficult to access, and there is a large range of motion. As a consequence, there are no readily available standard protocols or adapted systems for evaluating upper limb movements. The methods and processing tools used in gait analysis should be adapted, and specific parameters need to be developed for analyzing upper limb movements.

This article describes an automated procedure for (1) processing raw data from an infrared motion-tracking system, (2) identifying movement components, and (3) analyzing and presenting hand kinematic information in numerical and graphic outputs. This procedure was de-

veloped in Visual Basic 6 programming language, to be used on personal computers. This computerized procedure is called *Sarah-Pegworks*.

This method is based on the peg-moving task (PMT), which was initially proposed by Annett (1985) for the assessment of hand skill in children. Since then, the PMT has been widely used to study hand skill development and its relationship to cognitive development in children (Curt, DeAgostini, Maccario, & Dellatolas, 1995; Dellatolas et al., 2003). We used a reduced five-hole version of this task, consisting of a board with two rows of five holes (Figure 1).

METHOD

Instruments

A 12-camera motion-tracking system (Oxford Metrics Inc., U.K.) set at 250 Hz and a PMT adapted for this purpose (Annett, 1985; Dellatolas, Filho, Souza, Nunes, & Braga, 2005; Nunes, Braga, Lawisch, Nunes, & Dellatolas, 2008) were used to measure 3-D coordinates of markers located on a subject's skin. All the cameras were fixed in a circular roof structure at 2–3 m from the center of the capture area, as illustrated in Figure 2.

Fifty-five subjects, 27 men and 28 women, from 20 to 60 years of age (mean, 43.3 years), without any history of movement disorders, were studied with the motion-

Figure 1. Dimensions of the PMT-5: $195 \times 182 \times 45$ mm (hole diameter, 17 mm; peg, 54×15 mm; distance between rows, 131 mm; distance between holes of the same row, 37 mm).

Figure 2. Experimental setting for hand kinematics capture.

tracking system while performing the PMT-5 at the Sarah-Brasília International Center for Neurosciences and Rehabilitation. These data were used here to set the parameters for filtering, as well as movement identification.

Procedure

Fifteen retroreflective spherical markers (diameter, 14 mm) were attached to predetermined body sites: (1) sternum (sternal angle), (2) shoulder (acromion base), (3) elbow (olecranon), (4) wrist (styloid processes of the radius and ulna), (5) dorsum of the hand (metacarpals four and three), (6) nail of the thumb (ulnar side), and (7) nail of index finger (radial side). The pegs also had a reflective marker on their lower portion so that their trajectory could be identified. Figure 3 shows a schematic representation of the position of the retroreflective markers, and Figure 4 shows the markers attached to the hand and the lower portion of the peg.

The subjects sat in a chair appropriate to the task, and the tabletop was adjusted to facilitate a steady position (5 cm above the elbow). The pegboard was positioned at the midline, at forearm distance. The subject had to move

each of the five pegs, one by one, in a forward motion pattern, beginning with the peg at the side of each hand. The task started with the preferred hand, and the subject performed three complete trials with each hand. All the trials were videotaped, and the entire assessment could be completed within 10 min. The second complete trial of each hand was analyzed to allow movement stabilization and avoid further learning effects.

Filtering Raw Data

During the preprocessing stage, we verified the identification of the markers and the integrity of the data. Through synchronized videotaping and 3-D-reconstructed visualization of movement, we were able to ensure correct identification of the markers.

The motion analysis system produces a binary file in C3D format (Motion Lab Systems, n.d.) with time and 3-D coordinates for each retroreflective marker. These 3-D coordinates are the starting material for the processing stage. An example of raw data is presented in the Appendix. This type of data presents random errors, caused by interference in optical-electronic devices, video camera spatial resolution, and so forth, that must be corrected with the use of a smoothing technique.

One of the most widely used procedures for filtering human movement data is the Butterworth filter (Robertson & Dowling, 2003), as described by Winter (1990). A fourth-order zero-phase-shift filter was used to remove noise from raw data. The cutoff frequency was set by analyzing the residual signal amplitude (RMS) of filtered data. First, raw data were filtered at different frequencies (1–125 Hz), and the RMS was plotted. Figure 5 represents the curve for the residual noise effect.

Optimization of this filtering technique requires equilibrium between the reduction of the noise and the preservation of the true signal. To accomplish this, a linear projection was calculated on the basis of an adjusted line that had been obtained with 20 consecutive points ($R^2 > .99$),

Figure 3. Schematic figure of markers position. CLAV, sternum (sternal angle); SHO, shoulder (acromion base); ELB, elbow (olecranon); WRA/WRB, wrist (styloid processes of the radius and ulna); FIN, dorsum of the hand (metacarpals four and three); PO, nail of the thumb (ulnar side); IN, nail of index finger (radial side); PEG, inferior portion of the peg.

Figure 4. Hand sites for retroreflective markers and peg with inferior marker.

whose intercept indicated the RMS assigned to noise. This procedure permitted the identification of the cutoff frequency for each axis of the 3-D coordinates. The frequencies for the anterior-posterior axis were considered, since the displacements in this plane required a higher filtering frequency. Figure 5 illustrates this technique used to determine the cutoff frequency for 1 subject.

The cutoff frequency was defined as 15 Hz (interquartile distance: 13–16 Hz) on the basis of the analysis of 55 healthy subjects. The effect of the fourth-order But-

terworth filter at 15 Hz on the velocity profile of 1 subject is presented in Figure 6.

Identification of the Components of Movement

After the raw 3-D data have been smoothed, the movements and components of the PMT-5 need to be identified. The marker placed in the lower extremity of each peg was the initial reference for determining these movements. When the peg is located inside the target hole, the marker is not captured by the motion-tracking system. Consequently, the intermittent capture of these markers provides temporal references for determining the different components of each movement.

The task movements consisted of the successive repetitions of the transposition of the pegs, their insertion into the target hole, and the hand movements used to grasp the next peg. Each movement in the PMT-5 was divided into three components, as presented in Figure 7: (1) transport, (2) insertion, and (3) search (Curt et al., 1995).

Transport time. Transport time was defined as the time needed to transport the peg to the target hole. Transport time starts with the first of a series of 15 consecutive frames, with a positive acceleration of the thumb marker, and ends when the peg marker reaches the *target area*, defined as a hemisphere of 14 mm (the diameter of the marker) placed at the center of the hole.

Insertion time. Insertion time is defined as the amount of time taken to insert the peg into the hole. This moment starts one frame (4 msec) after the transport time and ends one frame before the start of search time.

Search time. Search time is the time needed for the hand to reach the next peg. This time starts at the first of a series of 15 consecutive frames, with a positive acceleration of the thumb marker, after the insertion of the peg into the target hole and ends 1 frame before the beginning of the next transport time. Search time includes the grasping of the peg.

Figure 5. Plot of the residual between a filtered and an unfiltered signal as a function of the cutoff frequency.

Figure 6. Velocity of the thumb marker. The solid line represents the velocity during the transport time filtered with a fourth-order filter. The dotted line represents the velocity based on raw data. f_c , cutoff frequency.

The hand velocity pattern during a complete trial of the PMT-5, with five transports, five insertions, and four searches, is presented in Figure 8.

Analysis and Presentation of Data: Parameters

Linear parameters were calculated on the basis of the thumb marker reference. Descriptive statistics were performed to determine time and linear parameters for each trial of the PMT-5. The parameters are (1) the time of execution of the components of the movement, (2) length of hand path, (3) velocity, and (4) grip aperture.

Time. Time was measured in seconds by the number of frames for each part of the task.

Length of path. The sum of each successive displacement of the thumb marker during the PMT-5 was calculated in centimeters as the length of the hand path:

$$p = \sum_{n=1}^N d_n,$$

where $d_i = \sqrt{dx^2 + dy^2 + dz^2}$ for $dx = x_i - x_{i-1}$, $dy = y_i - y_{i-1}$, and $dz = z_i - z_{i-1}$.

Velocity. The velocity in centimeters per seconds was calculated from displacement data, using nearby points on the basis of two time samples, as described by Winter (1990):

$$v_i = \frac{d'_i}{2\Delta t},$$

where $d'_i = \sqrt{dx^2 + dy^2 + dz^2}$ for $dx = x_{i+1} - x_{i-1}$, $dy = y_{i+1} - y_{i-1}$, and $dz = z_{i+1} - z_{i-1}$.

Grip aperture. During the search time, the grip aperture in centimeters was calculated as the distance between the thumb marker and the index finger marker.

Kinematic Report

Time normalization and averaging. Due to the repetitive and cyclic pattern of the PMT-5, the movements

were grouped to obtain a complete description of the task. Nevertheless, since the trials had different durations, the time scale had to be normalized. The percentage of movement duration was used to normalize the time scale for each movement component (transport time and search time).

In order to average the velocity for these movement components during the PMT-5, the mean value was calculated for the measures obtained at intervals of 2% movement duration. This time interval was used to avoid interpolation of data, since the duration of the movement components usually did not register more than 100 measurements.

The report presents the duration and linear parameters for each hand, movement, and component. For the transport time and search time, the parameters are (1) length of path, (2) mean velocity (average of instantaneous velocity), (3) the peak velocity (maximum instantaneous velocity), and (4) the mean grip aperture. Table 1 shows the means and standard deviations for these parameters in the group of 55 normal adults. An example of a kinematic report is presented in Table 2 with the results for a clinical case and a control case, comparing the right hand of both subjects.

Clinical Case Assessment

The patient (a 28-year-old right-handed male) had an ischemic stroke that resulted in bradykinesia with dystonic and choreic movements. The PMT-5 was used to evaluate hand function 1 year after the accident. A male subject of the same age, without motor deficits, also performed the PMT-5 and was used as a control.

The functional independence measure (FIM) scale was used to assess functional independence. The FIM is a 7-point scale with 18 items in several domains (self-care, sphincter control, mobility, locomotion, communication, and social and cognitive skills), which measure a patient's degree of disability and progress during rehabilitation (Keith, Granger, Hamilton, & Sherwin, 1987). Each item ranges from 1 (*dependence*) to 7 (*independence*). The self-care domain scores for this patient were the following: feeding, 5; grooming, 3; bathing, 3; dressing (upper body), 3; dressing (lower body), 4; and toileting, 1.

The results were obtained using the computerized processing presented here. Figure 9 details the velocity and grip aperture profiles for both subjects. The time scales were normalized in order to compare the patterns for each movement. As is shown in Table 2, the patient performance time was two to four times longer than the normal movement, and the search time was the most contrasting variable among the 2 subjects. Indeed, the velocity and grip aperture profiles are clearly different when the 2 subjects are compared. As is shown in Figure 9, the hand movements of the clinical subject were slower and more irregular than the movements of the control subject. We observed that a wider grip aperture was necessary even when the velocity was slower than expected, which is not observed in healthy adults performing an object-moving task (Grosskopf & Kuhtz-Buschbeck, 2006). This observation could help explain the kind of interference that made it difficult for this patient to tie his shoelaces, for example.

Figure 7. Velocity of the thumb marker during transport (A), insertion (B), and search time (C).

Figure 8. Velocity of the thumb marker of a right hand during a complete trial of the PMT-5. The vertical line indicates the endpoint of a complete movement represented in Figure 7.

Table 1
Hand Transport and Search Kinematic Parameters on the PMT-5 (*N* = 55)

Parameter	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Mean	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Transport												
Velocity (cm/sec)												
Right hand	44.2	8.6	45.6	8.1	47.7	9.1	48.1	8.9	47.8	9.2	46.7	7.9
Left hand	42.0	7.4	44.3	7.4	45.8	7.6	45.1	8.4	45.4	8.3	44.5	6.8
Length of Path (cm)												
Right hand	19.8	2.1	19.1	2.2	19.3	2.2	19.5	2.2	19.4	2.3	19.4	2.0
Left hand	19.3	1.9	19.8	2.2	19.6	2.5	19.8	2.5	19.9	2.4	19.7	2.0
Search												
Velocity (cm/sec)												
Right hand	55.3	14.1	55.2	11.6	53.8	11.4	55.7	12.6			55.0	11.8
Left hand	53.7	11.8	53.3	12.9	52.9	10.6	52.0	10.2			53.0	10.2
Length of Path (cm)												
Right hand	23.7	3.4	23.9	3.6	23.4	3.5	23.2	3.5			23.5	3.1
Left hand	23.1	3.4	23.1	3.5	22.8	3.0	22.3	2.6			22.8	2.9
Maximum Grip Aperture ^a (cm)												
Right hand	9.0	1.1	8.7	1.1	8.8	1.1	8.8	1.1			8.8	1.1
Left hand	9.6	1.3	9.4	1.3	9.2	1.2	9.2	1.2			9.4	1.2

^aDistance between thumb marker and index marker centers.

Table 2
Time and Kinematic Parameters for the PMT-5 Task

Time and Kinematic Parameters for the TMTS Task										
Trial	Time (sec)			Length of Path (cm)		Mean Velocity (cm/sec)		Peak Velocity (cm/sec)		Grip Aperture ^a (cm) (Search)
	Transport	Insertion	Search	Transport	Search	Transport	Search	Transport	Search	
Clinical Case										
1	0.760	0.316	1.488	16.87	35.91	22.20	24.13	36.08	67.99	5.49
2	0.984	0.512	1.364	18.33	23.87	18.64	17.49	33.69	54.05	7.04
3	0.976	0.712	1.216	18.66	26.32	19.12	21.65	41.14	45.93	6.66
4	0.956	0.400	1.816	20.28	33.27	21.23	18.33	40.77	69.54	6.54
5	0.872	0.384		22.39		25.69		43.79		
Control Case										
1	0.356	0.100	0.304	18.57	22.15	52.17	72.85	66.79	112.84	6.78
2	0.348	0.316	0.312	17.53	19.80	50.37	63.47	69.15	106.04	7.11
3	0.352	0.212	0.336	19.28	23.36	54.78	69.53	70.21	108.30	6.97
4	0.344	0.084	0.368	18.32	21.18	53.26	57.56	67.74	97.99	6.42
5	0.332	0.092		18.10		54.51		72.88		

Note—The parameters are relative to the right hand of both subjects. ^aMean grip aperture during search time.

Figure 9. Hand velocity and grip aperture curves for the clinical subject (left) and the control subject (right). The parameters are relative to the right hand for both subjects.

CONCLUSION

This work presents a computerized procedure called Sarah-Pegworks that is used to process and generate kinematic data. This procedure processes the raw data from an infrared motion-tracking system, identifies the movement components, and generates graphic and numerical output for research and clinical applications. Sarah-Pegworks was developed due to a lack of standardized, available methods for analyzing hand motion patterns during a PMT.

The motion patterns obtained in this work yielded results similar to, but more detailed than, those described in the literature (Biguer, Jeannerod, & Prablanc, 1982; Jeannerod, 1984, 1986). A first application in a brain-injured patient suggests that this method can provide information that is useful in clinical practice. For example, by tracking fine-motor movements in a patient with a specific deficit, one might be able to fragment the movement into its multiple components and understand the most "abnormal" component of an individual patient. Such analysis might help develop treatment strategies using various rehabilitation methods that can target the specific deficit identified by this system. The computerized procedure also permits angular analysis of upper limbs, not presented here.

In conclusion, this method for obtaining and processing kinematic data for upper limbs provides an objective assessment of hand skill and should serve as an effective tool for better analyzing, quantifying, and understanding movement disorders compromising hand function.

AUTHOR NOTE

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APPENDIX
Raw Coordinate Data of the Hand Transport (mm)

Frame	Time	Right Thumb Marker		
		<i>x</i>	<i>y</i>	<i>z</i>
799	3.192	104.42	243.87	86.47
800	3.196	104.80	243.58	86.78
801	3.200	105.29	243.18	87.09
802	3.204	105.78	242.78	87.49
803	3.208	106.29	242.45	88.09
804	3.212	106.93	242.07	88.91
805	3.216	107.64	241.74	89.88
806	3.220	108.32	241.54	91.01
807	3.224	108.95	241.34	92.37
808	3.228	109.59	241.08	93.81
...				
878	3.508	226.49	243.16	121.47
879	3.512	227.29	243.25	119.72
880	3.516	227.98	243.47	118.10
881	3.520	228.58	243.87	116.64
882	3.524	229.22	244.27	115.13
883	3.528	229.88	244.65	113.64
884	3.532	230.50	244.98	112.18
885	3.536	231.08	245.29	110.72
886	3.540	231.63	245.60	109.28
887	3.544	232.19	245.86	107.82

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