METHODS & DESIGNS

Gait analog tracings and computerized analysis through a PDP-11/45

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Human gait movements are measured and simultaneously recorded on an eight-channel magnetic tape recorder. An electrogoniometer is used for monitoring lateral, vertical, and anteroposterior displacements of the dorsal spine. Independent potentiometers detect arm swings and a microswitch circuit identifies the steps. Bursts of audio signals triggered to a preset cadence by an electronic metronome are presented at discretion to the subject through headphones in order to guide his step rhythm. Analog data for each walk session are digitalized at the rate of 20 samples/sec and stored on mag tape and/or disk along with the corresponding codes. Analyses of movement data are carried out on a PDP-11/45 computer.

Recent progress in computerized information processing has stimulated the development of specific softwares for the purpose of medical diagnosis and laboratory processing (Stacy & Waxman, 1965, 1969, 1974). Computer interpretation of electrocardiograms and electroencephalograms is a well accepted technique both in clinical research and in diagnosis (Dumermuth, Huber, Kleiner, & Gasser, 1970; Jacquez, 1972; Pipberger, Dunn, & Berson, 1975).

Although these applications have been known for a decade, the analysis of simultaneous complex analog signals remains a challenging problem. Human gait is of particular interest, since it implies various biological components such as body movement, velocity, and synchronism (Bouisset & Lestienne, 1974; Perry, Hoffer, Giovan, Antonelli, & Greenberg, 1974; Smidt, 1971; Wadsworth & Smidt, 1972). The clinical appraisal of gait is subjective and, as reviewed by Fregly, Smith, and Graybiel (1973), methods for recording and studying this phenomenon are still primitive. From the study of Winter, Greenlaw, and Hobson (1972), it is obvious that photooptic techniques are inaccurate for the process of the complex patterns involved.

This article describes an automatized method of recording and analyzing human gait patterns.

METHOD

Instrumentation

In order to generate specific signals produced by the gait of a subject, a multisensor system was developed from linear

potentiometers activated by mechanical gears (Figure 1). This electronic sensor setting is mounted into a platform sliding upon a rail. With this technique, there is no interference with movement of the subject. A continuous tracing for the position of the body is obtained by recording displacements of the subject simultaneously in three perpendicular axes: frontal, sagittal, and transverse. For this purpose the subject is attached by a scapular fixation to a lever connected with the platform. Lateral and vertical displacements of the cervicodorsal spine are monitored through the use of linear potentiometers; anteroposterior movements of the subject generate a rectangular wave produced by a photodiode circuit activated by the sliding of the platform.

Individual arm-swing recordings are obtained by using a scapular sensor that is sensitive only to the anteroposterior movements of the arm (Figure 1).

With a baro-microswitch system incorporated to a pair of shoes and with a logic circuit, foot contact with the floor is easily monitored by generation of a rectangular wave, permitting a specific differentiation between the contact of both feet and that of the left or right foot.

An electronic metronome is used to pace the subject wearing earphones. Upon hearing a rise in pitch, the subject is required to walk in synchrony with the metronome, to the best of his ability, toward a target. This stimulus is recorded simultaneously with the kinetic signals generated by the movements. Codification of the gait and identification of the subject are obtained with an electronic circuit that generates a train of five 4-bit binary numbers as well as the synchronization pulses (Figure 2).

All signals generated are monitored either on a Tektronix storage oscilloscope or by a light-emitting diode system, permitting a simultaneous check of the eight different signals to be recorded on an eight-track FM magnetic tape. The recorded signals are thereafter fed to a PDP-11/45 for digitalization and calculation of the selected gait variables.

Hardware

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Hardware consists of a PDP-11/45 computer with 28K of memory words, a RPO3 (20M words) disk, TM-11 mag tape, FP-11 floating-point processor, LS-11 line printer, LPS-11

Figure 1. Rail-suspended platform with integrated multisensor system coupled to an arm-scapular fixation unit through a rigid lever: Lateral and vertical movements of the breast-attached subject are transmitted to distinct gear-activated potentiometers; anteroposterior displacement induces sliding of the platform and activation of a photodiode circuit. Arm movements are separately monitored through gear-potentiometer couples.

Figure 2. Identification of the subject by five 4-bit binary numbers.

(A-D and D-A converters, clock, I/O registers, etc.), CRT display, and a hard-copy unit. The system runs under DOS/BATCH-11, Version 09-20C.

Computerized Gait Analysis

A program written in assembly language quantifies gait characteristics.

Analog data recorded for each different walk are digitalized at the rate of 20 samples/sec. This sampling frequency is chosen because body movements are slow and, in general, do not exceed 10 Hz (Sugano & Takeya, 1970). Sampling starts with an increase in signal pitch from the metronome and stops when the signals cease, the subject having reached the end of the test distance. The repetitive interval mode is used and each time the clock counter overflows, eight samples are sequentially taken from eight channels, occupying eight consecutive words of the data tables. The double-buffer method is used; that is, while the data from one table are being dumped to the storage device, new data are accumulated in the other table, so that no information is lost during the data acquisition. The data along with the identification codes are first stored on mag tape by blocks of 256 words each and then if desired, transferred onto the disk when the sampling is over. In practice, the mag tape is used as an intermediary medium for data acquisition. It is zeroed each time the data transfer to disk is terminated, so that only the first part of the tape is used. Otherwise, the

experimenter might wait too long for the rewind-forward sequence each time a new file is created.

Identification codes (Figure 2) are automatically decoded by the computer. The PDP-11/45 scans for the train of five synchronization pulses on Channel 0 and reads the corresponding 4-bit binary numbers (Channels 1 to 4) a few milliseconds after the onset of each synchronization pulse, taking into account the differences in setting times, if they exist, between the synchronization pulses and other signals.

After sampling is complete, data is displayed on the memory oscilloscope under program control, so that the evaluator can verify if the signals have been properly recorded and digitalized before proceeding to the next step.

Different gait variables are then evaluated. Since all data for each walk cannot be put into computer memory at the same time due to lack of space, two channels, at most, are analyzed at a time. Furthermore, the real position of the subject is obtained through trigonometric formulas based on the position of the platform along the rail, the angular position, and the length of the lever. The position of the platform is evaluated by accumulating algebraically the numbers of the positive (advancing) and negative (backing up) deflections of the rectangular wave (Figure 3). Finally, moments when the left foot, right foot, or both are on the floor are given by the three-level signal as described earlier (Figure 4). Correction for false steps due to rebounds of the baro-microswitches is made by computer software.

The results with the corresponding identification codes are stored in a file. This program occupies most of the 28K of memory words, the maximum workable space for DOS, including spaces for resident sections of DOS and tables of data.

Estimated Variables

Using the program described above, it is possible to determine the subject's reaction time as the interval between the increase in metronomic signal and the onset of the step response. Synchronism is calculated as the variation (standard deviation) in time intervals between the stimuli and their correspondent steps, omitting the first. The number and length of steps are readily obtained for each foot separately or for both feet. Regularity of the steps' length is estimated

Figure 3. Typical gait pattern under a moderate dose of alcohol showing hesitation. The subject swings backward (arrows in Tracing c) and makes a false step (arrow in Tracing d).

Figure 4. Typical gait pattern of a normal subject. In this figure as well as in Figures 6-8, the tracings as functions of time represent: (a) lateral movement, (b) vertical displacement, (c) anteroposterior displacement, (d) contact of the feet with the floor, (e) and (f) arm swings, and (g) signal from the metronome. All scales are arbitrary.

by the standard deviation of this variable. Rhythmicity in the movements of the feet is evaluated with the time intervals between the steps.

Arm swings are calculated in absolute amplitude and frequency; the average time interval between their maximum amplitude and the subsequent laying of the foot is determined to appraise the coupling of the arm-leg movements. Lateral and anteroposterior displacements of the subject from his resting position at the onset of the walk are determined to obtain the gait trajectory. Estimated slope of the latter and lateral deviation of the subject from the target to be reached are calculated as an index of orientation (Figure 5). Integration of gait trajectory provides an estimate of total distance walked and the difference from the length of the least-squares straight line can be considered as an indirect estimate of the coordination, since it increases when the subject is more unstable (Figure 5).

Position of the supporting foot at each step is estimated for the determination of the distance between the left and the right foot's trajectories. This distance provides an estimate of

Figure 5. Simulation of gait trajectory.

the width between feet during gait. Performance speed is calculated from the time required to walk the standard test distance. Vertical body oscillation is evaluated from the displacement of the shoulders in the frontal plane.

RESULTS

One hundred normal male volunteers, 18 to 38 years old (average: $25.10 \pm \text{SEM} = .50$), participated in an experiment where ethyl alcohol was randomly allocated at four doses: .0, .3, .6, or .9 g/kg. Figure 4 shows the typical gait pattern of a normal subject. Lateral displacements of the subject (Tracing a) show a regular oscillation due to alternate transfer of body weight from one foot to the other. The trajectory does not deviate significantly from the axis of the tracing prior to the walk. Vertical oscillations of the shoulders are illustrated in Tracing b. The absolute amplitude of these oscillations integrated in function of time showed a mean value of .288 msec. Tracing c illustrates the anteroposterior displacement of the subject along the rail axis. Contact of both feet with the floor is illustrated in Tracing d; right and left arm swings are represented in Tracings e and f. Finally, the signal of the metronome is shown in Tracing g.

Using data generated from Tracings a and c, the orientation and the coordination of the subject is mathematically appraised. A simulation of this procedure is presented in Figure 5.

Figure 6 illustrates a coordinated gait that is abnormal because of a right lateral deviation and exaggerated bilateral arm swings. Under the effect of a low dose of alcohol (Figure 7), the subject shows large lateral deviations with final correction for the

Figure 6. Gait with lateral deviation and exaggerated bilateral arm swings.

Figure 7. Typical gait pattern under a low dose of alcohol showing lateral deviation with correction.

target to be reached. With a moderate dose of alcohol (Figure 3), in addition to large lateral deviations, the subject presents some hesitation, swinging himself backward (the arrows in Tracing c) and making a false step (the arrow in Tracing d). The arm swings are irregular. Under the effect of a high dose of alcohol (Figure 8), the lateral deviations are more pronounced

Figure 8. Typical gait pattern under a high dose of alcohol. Lateral deviations are considerable but slow. The subject oscillates at the same place, swinging back and forth (arrows in Tracing c) and making false steps (arrows in Tracing d).

but less rapid. The subject may lose his balance. In this example, he oscillates at the same place, swinging back and forth (the arrows in Tracing c) and making false steps (the arrows in Tracing d). This phenomenon is also reflected by a relatively large vertical shoulder movement (deflection in Tracing b). The arm swings have practically no relationship with the steps.

DISCUSSION

The dose-related effects of ethanol on gait were documented electronically. Like results were obtained in experiments with marijuana and dextroamphetamine and with a new benzodiazepine.

The foreseen applications of this new technology are numerous. For instance, in clinical neurology, syndromes such as Friedreich's ataxia, Huntington's chorea, and multiple sclerosis can be evaluated and documented in a much more precise and objective fashion. Furthermore, the patients' follow-up is made easier, and the efficacy of their treatments better assessed. Drug-related effects on coordination can also be characterized.

REFERENCES

- BOUISSET, S., & LESTIENNE, F. The organization of a simple voluntary movement as analysed from its kinematic properties. *Brain Research*, 1974, **71**, 451.
- DUMERMUTH, G., HUBER, P. J., KLEINER, B., & GASSER, T. Numerical analysis of electroencephalographic data. *IEEE Transactions on Audio and Electro-acoustics*, December 1970, **AU-18** (4), 404-411.
- FREGLY, A. R., SMITH, M. J., & GRAYBIEL, A. Revised normative standards of performance of men on a quantitative ataxia test battery. *Acta Otolaryngologica*, 1973, **75**, 10.
- JACQUEZ, J. A. (Ed.). *Computer diagnosis and diagnostic methods*. Springfield: Charles C. Thomas, 1972.
- PERRY, J., HOFFER, M. M., GIOVAN, P., ANTONELLI, D., & GREENBERG, R. Gait analysis of the triceps surae in cerebral palsy: A preoperative and postoperative clinical and electromyographic study. *Journal of Bone and Joint Surgery*, 1974, **56**, 511, (AM).
- PIPPERGER, H. V., DUNN, R. A., & BERSON, A. S. Computer methods in electrocardiography. *Annual Review of Biophysics and Bioengineering*, 1975, **4**, 15-42.
- SMIDT, G. L. Hip motion and related factors in walking. *American Physical Therapy Association Journal*, 1971, **51**, 9.
- STACY, R. W., & WAXMAN, B. D. (Ed.). *Computers in biomedical research* (Vol. 1-2). New York: Academic Press, 1965.
- STACY, R. W., & WAXMAN, B. D. (Ed.). *Computers in biomedical research* (Vol. 3). New York: Academic Press, 1969.
- STACY, R. W., & WAXMAN, B. D. (Ed.). *Computers in biomedical research* (Vol. 4). New York: Academic Press, 1974.
- SUGANO, H., & TAKEYA, T. Measurement of body movement and its clinical application. *The Japanese Journal of Physiology*, 1970, **20**, 296-308.
- WADSWORTH, J. B., & SMIDT, G. L. Gait characteristic of subjects with hip disease. *American Physical Therapy Association Journal*, 1972, **52**, 831.
- WINTER, D. A., GREENLAW, R. K., & HOBSON, D. A. Television computer analysis of kinematics of human gait. *Computers in Biomedical Research*, 1972, **5**, 498.

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