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METHODS & DESIGNS

Computer-analyzed measures of characteristics of human locomotion and mobility

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Path and speed characteristics of human locomotion were detected by a mechanical sensing system and processed by a digital computer to give graphical and numerical measures of performance. The problems of deriving such indices are discussed, and a number of simple experiments are included to demonstrate that these measures yield dependent variables suitable for use in the study of the perceptual information required for mobility and locomotor control.

The ability of a person to control the path of his body in space is a basic perceptual-motor skill that has received little objective study. Yet it is probably the most common application of the skills of space perception, often requiring rapid and accurate spatial judgments as well as the ability to predict both one's own travel path and the paths of others. If a person suffers a severe visual handicap, the loss of travel skills becomes one of the most obvious rehabilitation problems. Extensive training in the nonvisual senses, plus the use of an aid such as a guide dog, cane, or electronic sensing aid, can provide a blind person with enough travel ability to live an independent life. But the gracefulness of sighted travel is seldom achieved and the freedom of the sighted person to travel anywhere, with ease, is virtually never encountered.

Very little information exists at the present time on the study of purposeful locomotion, outside of the speculative accounts of Gibson (1958, 1966). Experimental work is difficult to conceptualize and even more difficult to quantitatively assess. In a previous paper (Strelow, Brabyn, & Clark, 1976), a system for monitoring and recording locomotor performance was described. The prime concern of the present article is the nature of the measures this system provides when the data are analyzed on-line by a digital computer.

THE MEASURING SYSTEM AND DATA ANALYSIS

The essence of the measuring system is the continuous monitoring of the position of a subject in a large laboratory by three very light lines attached to take-up drums around the walls. The tension in the lines and the inertia of the system as a whole is kept to a minimum, allowing accurate position sensing with little impediment to the subject's movements.

A photocell arrangement around two of the drums allows movements of the drums, corresponding to the subject's movements, to be sensed, and produces a stream of digital pulses. These are counted using digital logic, allowing a binary word representation of the length of each line (see Figure 1). This data can go directly to a digital computer (see Strelow et al., 1976, for further details of the apparatus and alternative data processing). The digital computer can sample the binary words representing line length at rates up to 60 Hz, although the normal rate is 5 Hz. These data are converted to x and y coordinates of the subject's position by the repetitive solution of two equations relating line extension, from the sensing drums, to true position in the room.

This position information is plotted on a storage oscilloscope and the data points are retained in the computer memory for subsequent analysis. Figure 2 presents a flow chart description of the data processing sequence in the computer. By appropriate Teletype commands, the scale of the display and the portion of the room displayed can be varied at will. Timing of each experimental trial is performed by the computer's internal timer and is started and stopped by pushbuttons.

GRAPHICAL AND NUMERICAL PERFORMANCE MEASURES

The most basic performance information obtained from the system is the plot of the subject's path, marked with crosses representing constant (1-sec) time intervals. The positions of various obstacles can be recorded on this plot by typed commands or by direct use of the sensing linkage. Figure 3 shows an example of such a

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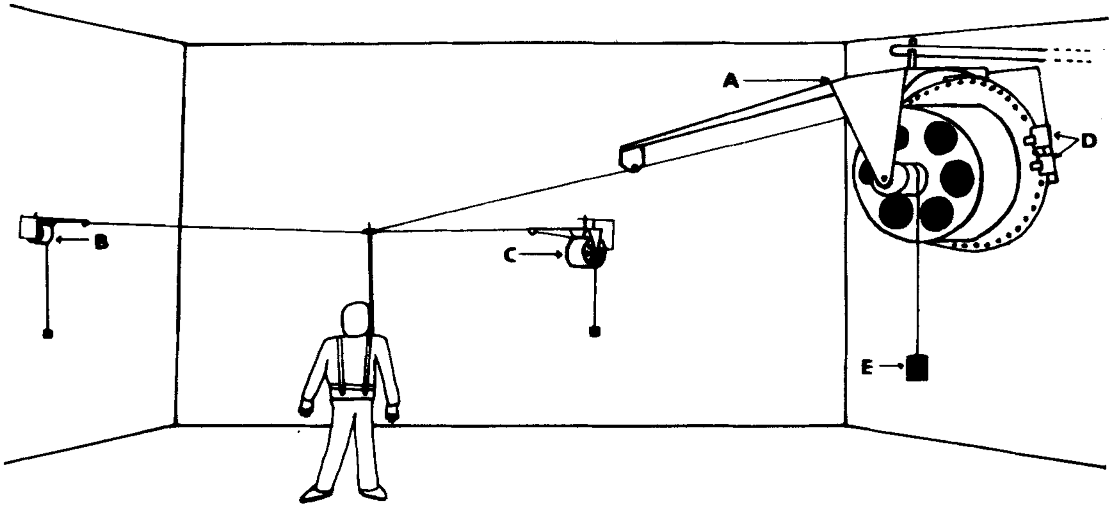

Figure 1. Drawing of mechanical sensing arrangement showing two sensing drums (A and B) and third balancing drum (C). Closeup of drum (A) shows photocell pair (D) and geared pulley with tensioning weight (E). The subject is shown with harness for fastening the pole to his back.

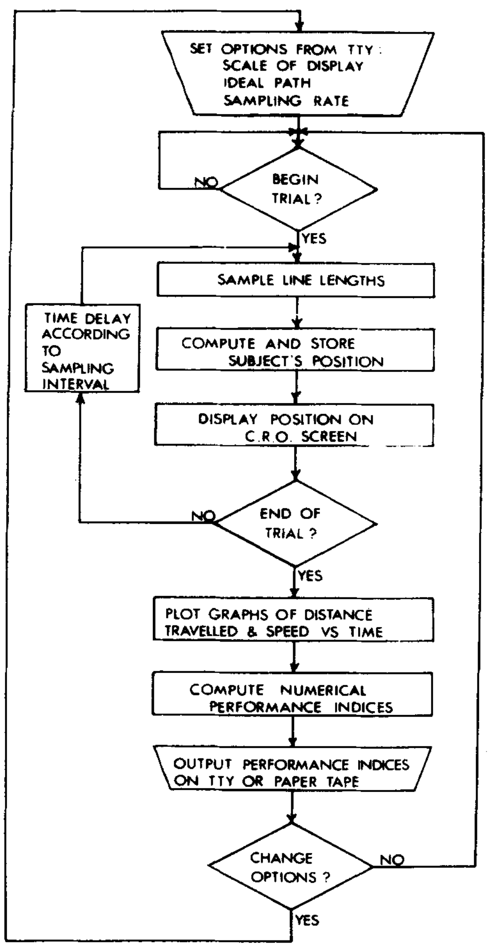

Figure 2. Flow chart of data processing sequence on the digital computer yielding graphical and numerical performance measures.

plot when a subject was required to walk around a square delineated by four corner poles. The proximity of the path to these obstacles can be measured directly from the graph.

In Figure 4, speed has been plotted, in this case, for a subject walking along a straight path. Successive footsteps were taken every 2/3 sec on command to a 1.5-Hz pulse train generated by the computer. The pulses were transmitted to the subject through headphones, and the instant at which each pulse occurred was encoded by a spike on the speed-vs.-time graph. The deviations in speed are specifically related to each step, speed reaching a maximum as each step hits the ground and reaching a minimum at midstep. (The relationship between speed deviations and the footsteps appears to be typical of observed performance in the laboratory irrespective of whether or not metronome pulses are used.)

While such graphs can be used to provide experimental data, they do not easily lend themselves to experimental studies with groups of subjects. For this purpose we developed a selection (from a potentially infinite set) of numerical indices that would describe aspects of performance for a given experimental trial. Initially, these were based on the subject's speed and trajectory.

Average Speed

The first numerical characteristic to be computed is average speed (AVSP). The distinction between speed and velocity should be noted. Whereas velocity is defined as vector displacement per unit time, speed is total path length (regardless of direction changes) per unit time. Thus, in measuring speed, no assumptions need be made about straightness of the path or ideal direction of travel. The total path length is computed by scalar summing of the individual displacement magni-

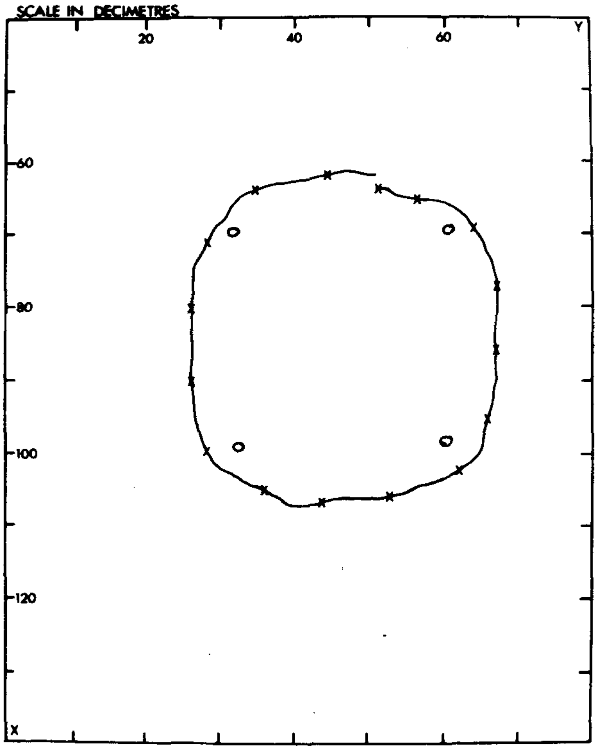

Figure 3. A position plot of the path of a sighted subject instructed to walk outside the perimeter of a square whose corners were marked by the four circles. The crosses indicate 1-sec time intervals.

tudes occurring during each sampling interval. This sum is then divided by the elapsed time to produce mean speed.

Care is needed in interpreting the mean speed measure, for while very slow performance indicates poor mobility, competent travel is likely to be characterized by moderate speed, not necessarily the maximum of which a person is physically capable.

Deviations from Average Speed

Speed shows marked within-step fluctuations even for travel along a straight path (see Figure 4). Gross overall speed variations can also occur under some conditions (e.g., Figure 5b), and could indicate poor perceptual-motor control.

One means of assessing speed deviations is to measure average acceleration (AVAC). This is computed by taking the speed for any given sampling interval and subtracting from it the speed for the previous interval. Dividing this value by the duration of the sampling interval yields acceleration, the modulus of which is taken and the mean computed over all sampling intervals.

An alternative approach is to measure the deviations of speed from the average value for a given run. By squaring this deviation for each sampling interval, taking the mean over all intervals, and, finally, taking the square root, the root-mean-square deviation from average speed is computed (RMSDAS). The rms value is preferred to a simple mean because it weights more heavily large excursions away from mean speed such as occur during collisions.

While it might appear that the two measures of speed deviations detect similar aspects of performance, they actually emphasize different characteristics. Rapid and frequent changes in speed can give rise to large AVAC values. However, if the subject's speed does not remain for long at peak and minimum values, RMSDAS will not be correspondingly large. Figure 5 shows examples where AVAC and RMSDAS are not highly correlated. By retaining both measures, greater precision is possible in describing actual performance.

Path Deviations

The first three measures characterize forward body motion; the remaining measures describe lateral or side-to-side characteristics. These measures are chosen to detect improper body control which can lead to deviations of the body path from an optimal characteristic. Two approaches were tried. In one, the ideal path was specified before the subject began walking. This is reasonable for many tasks; for example, a subject may be positioned 1 m from a wall and asked to walk parallel to this wall. The ideal path is thus a straight line 1 m from the wall and parallel to it. The rms value of the perpendicular distances of the sampled positions, from the ideal, yields a measure of rms deviation from the ideal path (RMSDIP).

Alternatively, if any straight path is acceptable, as

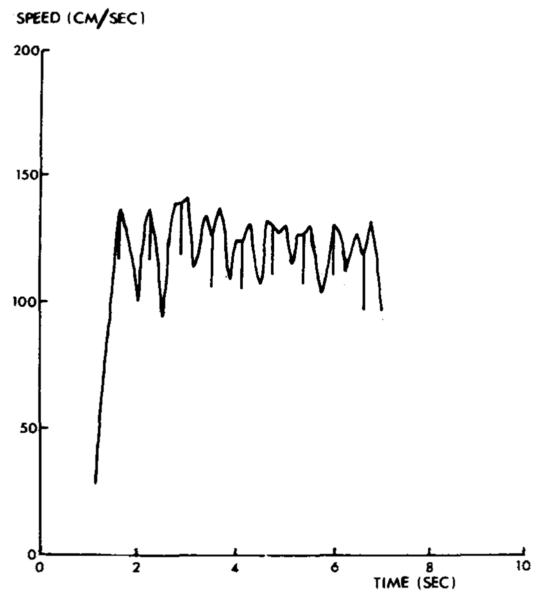

Figure 4. Speed characteristic for a subject walking in time to a 1.5-Hz metronome beat. The vertical strokes indicate each beat and, thus, each footfall.

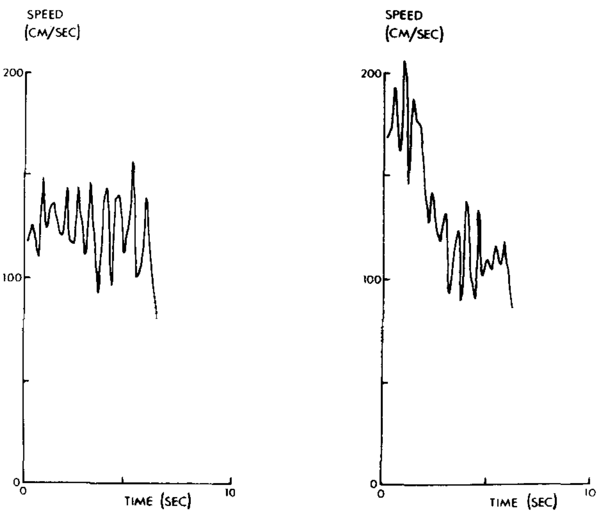

Figure 5. Two examples of speed plot illustrating different RMSDAS values while AVAC remains largely unchanged. In 5a RMSDAS = 17.5 cm/sec and AVAC = 108 cm/sec²; in 5b RMSDAS = 32.7 cm/sec, while AVAC = 113 cm/sec².

long as it if parallel to the wall, an ideal straight line can be fitted by taking the average value of coordinates perpendicular to the wall. The rms deviation from this straight line (RMSDSL) can be computed.

While the RMSDIP measure penalizes a subject for any deviation from the specified ideal, the RMSDSL measure is tolerant of the subject who travels in a straight line but prefers to set his own distance to travel from the wall. It can be seen, then, that, in the cases of both speed and path deviations, optional forms of measurement can be established to test for subtle, but important, distinctions in performance.

Path Curvature

When a subject is asked to walk around a square (Figure 3), he will tend to round the corners. There is a sense in which this observed travel may be ideal for the subject even though it does not conform to a geometric ideal.

The measure of surplus curvature (SCURV) was developed to provide a performance index which is not closely tied to geometrically ideal path shapes. The algorithm sums the incremental angles (Figure 6) between sample steps, ignoring signs, giving the total angle turned by the subject's trajectory. From this value, the minimum amount of necessary turning is subtracted. For example, in traveling a straight line, 0 radians is the ideal minimum turning, while 2π radians is ideal for a circle or square. After this subtraction, the resulting surplus turning is divided by total path length to yield SCURV, in radians per meter. This measure allows easy changeover from one path to another whether they differ in size or in shape.

SYSTEM LIMITS

Before attempting to characterize the performance of the human body in locomotion, it was necessary to assess limitations in the accuracy of the on-line monitoring system. It was previously demonstrated (Strelow et al., 1976) on the basis of calculations and measurements that the static position error was less than 2.5 cm within a measuring region of 80 cm². In the dynamic case, a mathematical analysis predicted that an acceleration of .3 g could be tracked without exceeding the 2.5-cm margin of error. The response of the system was tested, in practice, by attaching the linkage to a mechanical driver moving in an approximately sinusoidal manner, with a frequency of .7 Hz and an amplitude of 30 cm. The position plot obtained on the oscilloscope is shown in Figure 7. There is a good correspondence to a sine wave, although the maximum acceleration is .4 g (i.e., 4 m/sec²).

In the second test, both the sensors and computer algorithms were tested in terms of their ability to register linear motion over a distance of 5 m. The test motion was produced by attaching the linkage to a wire, stretched taut, between two pulleys, one of which was driven by an electric motor to move the linkage at 100 cm/sec. The linearity of the system was assessed by computing the RMSDSL and SCURV measures. The former showed values of .3 to .5 cm, while the latter varied from .12 to .18 radians/meter. These are a good deal less than the values obtained for actual mobility performance (see Table 1). Even the lowest values of path deviations (e.g., RMSDSL) for good, sighted performance appear to be well above the measurement threshold of the system. The values obtained in this mechanical test were most likely to be overestimates of error, in any case, because of a residual sideways oscillation of the moving wire.

DEMONSTRATIONS OF MOBILITY PERFORMANCE

In the first set of demonstrations, three tasks were chosen to represent some of the common characteristics of mobility. The purpose was to assess the typical numerical values obtained by normal, sighted subjects

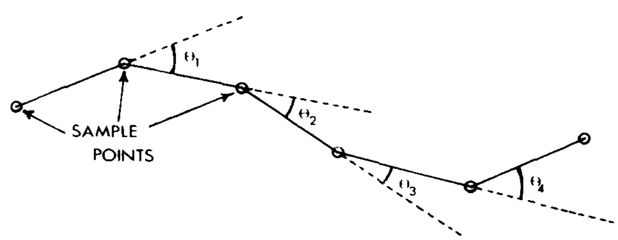

Figure 6. A representation of the means by which the SCURV algorithm totals the amount of turning of the subject's path of travel. The circles represent sample points 200 msec apart. $\theta_1 \ldots \theta_4$ represent angle of turn from one sample to the next.

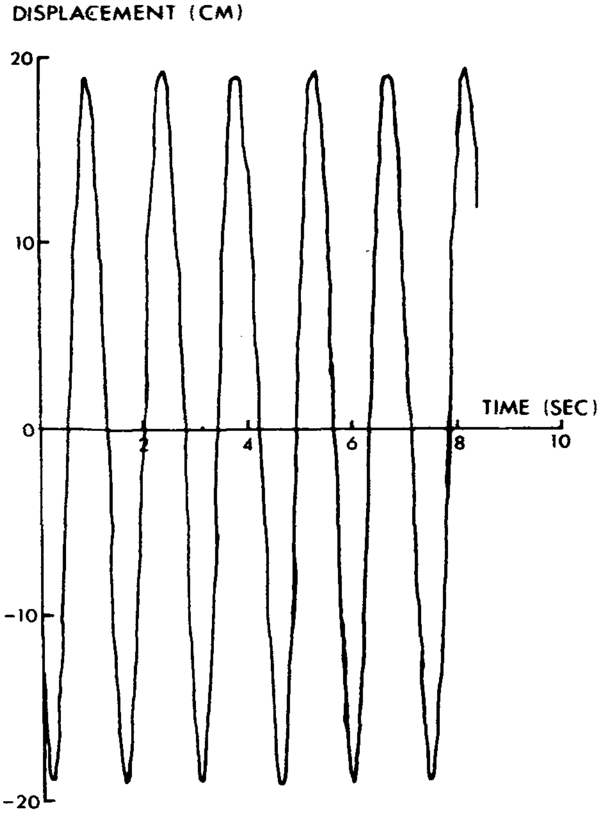

Figure 7. Oscilloscope record of the computed motion of the sensing linkage when driven by a mechanical driver at a .7-Hz oscillation with accelerations up to .4 g.

and the variability of these measures from trial to trial and across subjects. In experimental settings, these conditions typically provide the baseline against which the conditions of nonoptimal perceptual control information would be compared. In the second set of demonstrations, the perceptual information for accurate locomotor control was impaired by requiring subjects to perform with degraded vision, or by auditory control. The numerical measures were shown to be capable of differentiating these latter performance conditions from the normally sighted condition.

VISUAL CONTROL TASKS

In the first task, subjects were asked to walk toward a target 10 m distant. In the second task, subjects were required to walk in a slalom fashion around six poles, placed 2 m apart, and to keep approximately at arm's length from the poles. In the third task, subjects were required to walk around eight poles, arranged in a circle 4 m in diam, again staying at arm's length from the poles. The tasks chosen thus required steady locomotor control (straight line task), rapid path alterations (slalom), and gradual path changes (circle) in response to visual spatial information.

Six subjects performed each task 10 times, with each subject performing the three tasks in a different order. Subjects were asked to walk as normally as possible. However, early experience indicated that subjects showed considerable variability in interpreting this instruction, with some subjects traveling at a pace close to running. Accordingly, some control over speed was obtained by requiring subjects to walk in time to a metronome set to 1.5 Hz, a typical walking cadence (Contini, Gage, & Drills, 1965).

The numerical measures are shown in Table 1. The RMSDIP and RMSDSL measures are strictly applicable only to straight line travel, but were also computed for the slalom merely to indicate that these measures are sensitive to gross path changes.

The standard deviations are reasonably small both within and across subjects, indicating consistency of performance, although greater variability could be expected if the stepping rate was not set by a metronome. The magnitude of these measures depends on the nature and positioning of the mechanical linkage as different parts of the body move in different patterns (Contini et al., 1965). The previous conditions were repeated for a further six subjects using a linkage attached to the top of a small adjustable helmet worn on the head, in the expectation that this linkage would register less body sway than one mounted on a pole some distance over the subject's head.

The results are shown in Table 2. While speeds were higher for these subjects than for the previous six, most measures of path and speed variability were reduced,

Table 1
Sighted Performance: Pole Mounting

	Straight Line			Slalom			Circle		
	Mean	σ_1*	σ_2	Mean	σ_1	σ_2	Mean	σ_1	σ_2
AVSP (cm/sec)	95.5	3.0	7.4	78.4	1.75	2.4	91.1	2.8	6.2
AVAC (cm/sec^2)	57.8	9.4	11.7	58.6	6.7	12.6	59.5	2.8	10.8
RMSDAS (cm/sec)	9.8	1.2	1.9	11.4	1.0	2.0	9.8	1.2	1.6
RMSDIP (cm)	7.5	2.5	2.0	47.7	2.3	7.4			
RMSDSL (cm)	4.0	.7	.7	47.0	2.2	7.3			
SCURV (radians/m)	.798	.114	.169	1.664	.139	.322	.870	.117	.213

*σ_1 = *mean standard deviation of within-subjects variability;* σ_2 = *standard deviation of mean scores across subjects.*

Table 2
Sighted Performance: Head Mounting

	Straight Line	Slalom	Circle
AVSP (cm/sec)	106.9	83.7	102.7
AVAC (cm/sec²)	39.8	40.6	41.9
RMSDAS (cm/sec)	7.6	8.5	7.5
RMSDIP (cm)	7.0	57.6	
RMSDSL (cm)	3.2	56.8	
SCURV (radians/m)	.359	1.101	.416

with surplus curvature in particular being affected.

It appears that head mounting can result in lowering the basic deviation indices, and it could increase the sensitivity of experimental conditions. But this is done at the cost of introducing detectable forces at the subject's head. Whereas a resultant force of 50 g was required with back mounting before its direction could be sensed (Strelow et al., 1976), only 10 g was found to be required with head mounting. An additional disadvantage is that, if tall obstacles are introduced in an experimental setting, there is some danger of these snagging the measuring lines. On the other hand, the forces on the subject's head, while above threshold, are by no means obvious, nor do they result in fatigue when head mounting is used. Also, the head mount is easier to take on and off than the back mount. Finally, the position bias possible with head mounting can usually be discounted as a factor in experiments by the use of appropriate control conditions. If, however, this form of bias must be reduced to an absolute minimum, then back mounting is preferable.

LOCOMOTOR CONTROL WITH DEGRADED PERCEPTUAL INPUT

Finally, an experiment was performed to test the ability of the computer-coupled monitoring system to discriminate between good and poor performance in a given task when the perceptual control information was degraded. Six subjects were used, with head mounting.

The task of walking straight toward a target was investigated under three different conditions of sensory input: sighted performance and two conditions expected to be more difficult, namely, degraded vision and auditory control.

In the normal vision condition, a pole at a distance of 10 m was the target of approach. In the degraded vision condition, a light was mounted at a height of 1.6 m on the pole and the room was darkened. A facemask of diffusing glass reduced the subject's perception of the target light to a blur extending over 30-40 deg of the visual field. In the auditory condition, the light was replaced by the metronome (used in all cases to control the rate of walking) mounted at the same height and set to 1.5 Hz. The subject was blindfolded and instructed to walk toward the sound source. Every subject again performed each task 10 times with a different order of conditions.

The results are presented in Table 3 along with indications of statistical significance. Average speed was down for the conditions of degraded perceptual input, while the measures of deviations in speed and path trajectory increased. Significant differences between normal visual control and degraded vision, or auditory, control were noted for all measures except AVAC and SCURV. This confirmed the expectation that conditions of degraded input would result in performance measurably different from normal visual control. From the standpoint of perceptual-motor control, any increase in such deviations must be regarded as indicating poorer performance. The reduction of speed for the conditions of degraded input could also indicate a greater difficulty in these conditions (however, see above discussion on average speed). From these results, therefore, it seems fair to conclude that the monitoring system meets the prime requirement for the study of mobility and perceptual-motor performance, namely, that it can detect subtle losses of motor control.

GENERAL DISCUSSION

The main use of the measuring system is to enable a quantitative assessment of the ability of subjects to use restricted perceptual information to control their body movements; the final experiment is closest to the typical research application. In the applied sphere, the system allows assessment of the usefulness of electronic sensing aids for blind mobility. The indices chosen were felt to be suitable for these purposes, although for other purposes other indices could be derived. However, the measures chosen are not entirely arbitrary. Measures of speed and path deviations, particularly when applied to studies of normal visual control, quantify fundamental characteristics of human gait. The system and measures may therefore be useful for the other types of study. An application already being exploited is the investigation of deterioration in locomotor performance caused

Table 3
Locomotor Control with Visual, Auditory, and Degraded Visual Control Information

	Normal Vision	Auditory Control	Degraded Vision
AVSP (cm/sec)	113.5	102.8*	103.2**
AVAC (cm/sec²)	32.5	35.8	35.9
RMSDAS (cm/sec)	7.2	10.9*	10.2**
RMSDIP (cm)	6.6	21.5*	19.7***
RMSDSL (cm)	3.4	9.7***	8.4***
SCURV (radians/m)	.377	.429	.499

*Note—For no measures were there significant differences between auditory control and degraded vision. Statistical differences between either of these and normal vision [t(5), two-tailed test] are noted as follows: *p ≤ .05, **p ≤ .02, ***p ≤ .01.*

by the intake of alcohol. The system may also be useful to define normal gait so that the use of limb prosthetics can be assessed.

Recent development of the system has allowed computer simulation of blind aids with auditory or tactile displays. This has involved using the digital computer to control an analog computer which is programmed with the display characteristics of the system under study. In the case of an auditory display, for example, the sound patterns of a simulated electronic sensor can be fed to the subject through earphones as he moves around the laboratory. The digital computer can be programmed to present obstacles, as well as providing the measurements of performance noted above.

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