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ACCELEROMETRY—A TECHNIQUE FOR THE MEASUREMENT OF HUMAN BODY MOVEMENTS*

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Abstract—A summary of the indications for new systems of measurement is given, with particular reference to the advantages and potential hazards in the use of accelerometers. A study of the movement of the shank, or lower leg, using accelerometers is reported. The paper concludes that improved transducers will allow this method to be extended to the study of the movement of other parts of the body. An Appendix shows how the signals from six accelerometers may be used to define completely the movement of a body in space.

INTRODUCTION

MANY bioengineers involved with the study of human movement have at some time attempted to use an accelerometer for that quantitative measure of that movement. Some of the attempts have been reported (Saunders *et al.*, 1953; Gage, 1964) but, certainly, by far a larger number are remembered only as failures. The probable reasons for these failures are worth examining, because, in many areas, the potential advantages of accelerometry over kinephotography (Sutherland *et al.*, 1972), electrogoniometry (Kettelkamp *et al.*, 1970) and other current methods appear numerous.

Probably the commonest cause of failure with the method is the use of an unsuitable transducer. Most applied mechanics laboratories possess a piezoelectric accelerometer designed for the study of vibration and it is usually this device which is first used by the experimenter. Since these devices might more properly be called 'jerkometers', needing as they do a charge-integrating amplifier in order to measure acceleration, the benefit of their small size is often lost. Furthermore, the absence of a true steady-state response and the low sensitivity of such devices make them wholly unsuitable for the examination of muscular-controlled movements.

Inertial guidance systems use transducers of the 'force-feedback' type with a steady-state response and high sensitivity but again the bulk of the associated electronics and the enormously high price of such accelerometers makes them unsuitable. Strain-gauge accelerometers which deform elastically due to inertial force are certainly the most suitable type of transducer, and these are available at low cost in a variety of configurations. A cantilever type with semiconductor strain elements was used in the experiments reported here.

Another reason why accelerometry has not been more widely used in biomechanics is the widespread misconception that, by analogy with inertial guidance, gyroscopes are needed for the measurement of angular movement. The true situation is quite different. Gyroscopes are used in aerospace inertial guidance precisely because the movements are largely translational, and rotations are small and slow, and therefore difficult to measure. In gait, however, the acceleration of a point of the leg is normally due largely to rotational movements with the translational components becoming large only when the system is changing the number of its degrees of freedom by contact with the external environment. It is

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sufficient that six simultaneous independent measurements are made of the translational components of the movement of a rigid body, moving unconstrained in three-dimensional space, for the movement of that body to be determined absolutely with respect to a reference coordinate system. These six measurements can all be made with accelerometers. (See Appendix).

The study of all animal movement is complex both analytically and numerically. The analysis may be simplified by approximations such as rigid-body assumptions, but the numerical effort involved is always considerable. The use of digital computation is therefore clearly indicated. Furthermore, biological data is often ill-ordered and unpredictable, and the ability of the experimenter to interact with the automatic computational process in order to make algorithmically complex decisions contributes a great saving of time and effort.

The particular study reported here involves the examination of the movement of the lower leg, or shank. The aim was to develop a system of measurement suitable for both experimental and clinical use which could be operated simply and with minimal disturbance of gait in situations outside the biomechanics laboratory.

A well recognised difficulty associated with the kinephotographic measurement of gait has been that encountered in the single and double differentiation of position data with respect to time. There are numerous sources of noise at the upper end of the frequency spectrum of the data (Gutewort, 1971). Since these noise components are preferentially increased by time-differentiation, the signal-to-noise ratio of the data is decreased. Whenever accelerations have been obtained from photographic position data, relatively severe mathematical filtering has been employed (Paul, 1965) so that the transfer function of the differentiation process has a frequency spectrum as shown in Fig. 1. The break-point, ω_0, is chosen as the highest frequency compatible with subjectively noise-free velocity and acceleration. The value of ω_0, which would allow true differentiation of the whole signal band is almost certainly higher than that normally used.

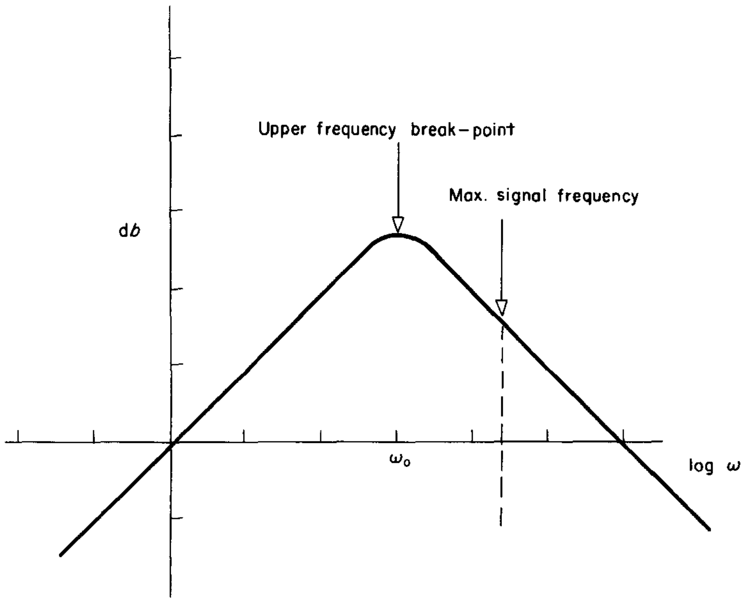


Fig. 1. Band-limited Time-differentiation, showing a possible discrepancy between the differentiation break-point and the maximum significant signal frequency.

An analogous noise problem occurs when acceleration is measured and then integrated to determine velocity and position. The noise frequency which is then the most significant is the lowest. However, in gait analysis, the lowest signal frequency of interest is known to be the double-step frequency. Cutting-off frequency components below this value prevents the determination of the moving body's absolute position in space. But more important is the knowledge of movements within a double-step and this can be determined with considerable accuracy.

METHOD

A detailed algebraic description of the analysis procedure is given in the Appendix. Only such details as are necessary to give a description of the technique are included in this section. Accelerometers of the type shown in Fig. 2 are used to obtain data on the accelerations of the leg between knee and ankle. The net acceleration field, due to movement and gravitation, causes the cantilever to bend in the plane of the sensitive axis. Mean signal-to-noise ratio within the signal frequency band is better than 40 db. Five accelerometers are mounted on the perspex platform shown in Fig. 3. No attempt is made to measure transverse rotations of the shank. Such measurements would require a larger dimension of the platform in the plane normal to the long axis of the accelerometer platform. Since such rotations are relatively small (Levens *et al.*, 1948), they may reasonably be assumed to be zero. However, results so far obtained with five transducers are good enough to suggest that the inclusion of a sixth to allow measurement of transverse rotations would be justified and this improvement is planned.

The platform is mounted over the flat, antero–medial surface of the tibia. Silicone rubber caulking is coated onto the contact side of the platform to provide a high friction interface and the platform is held in place by a moulded "Plastazote" cast also coated with silicone rubber. The effect of the mounting technique is to provide heavy mechanical damping between the accelerometers and the shank.

Signals from the accelerometers can be recorded either on a portable subject-carried tape recorder, or passed by a lightweight cable to a fixed recorder.

The entire analysis of the signals is done on a small interactive digital computer with analogue input facilities and a visual display. The data is first searched visually for an event of particular interest, and a period of 2·56 sec real-time data is selected and sampled at 10 msec. intervals, and digitised. One cycle of any periodic function can be clearly recognised on the computer v.d.u. and cursors set to mark the beginning and end of a cycle. Such

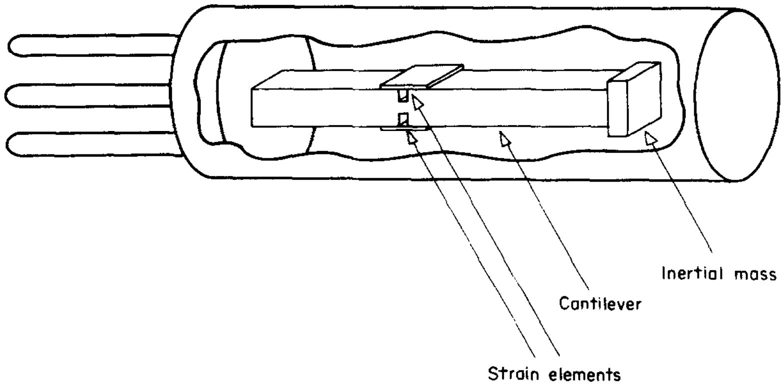
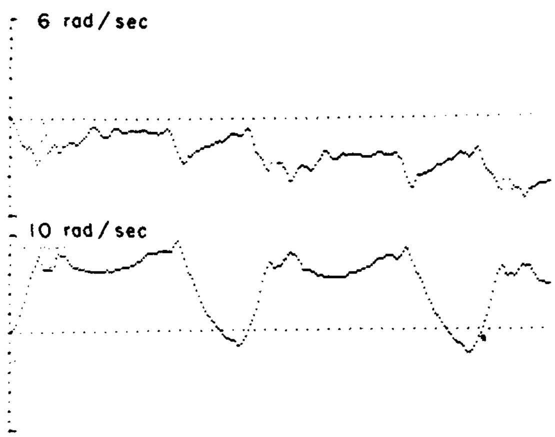


Fig. 2. A schematic representation of the type of accelerometer used. (The length of the cylindrical casing is 14 mm).

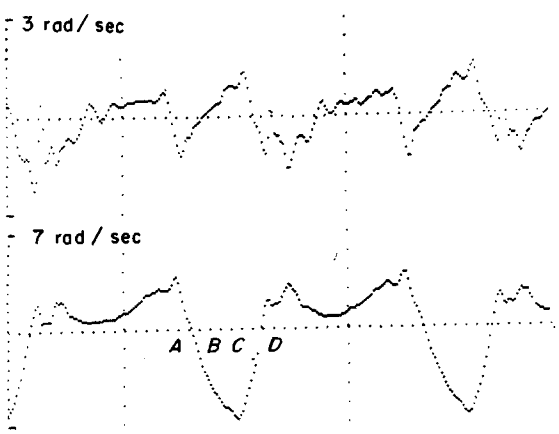
functions (Fig. 4a) are then filtered mathematically (Fig. 4b) to make their values equal at the beginning and end of the cycle. This process removes drift and sets a lower frequency limit on the signal pass-band corresponding to the double-step period.

The stance phase of the walking cycle can generally be divided into three distinct periods. The first, immediately following "heel-strike", is short and lasts until the foot is flat on the ground. The second, or "foot-flat" period lasts until "heel-off" and is of approximately the same duration as the third period, which lasts from "heel-off" until "toe-off". During the second period the shank of the leg moves with pure rotation about a point whose position is known. This point lies within the talus between the axes of the ankle and subtalar joints (Wright *et al.*, 1964). Since the position of this origin of rotation is known, the knowledge of the motion of the shank becomes mathematically redundant. The six parameters of motion which are measured or assumed to be zero are not then independent. Their interdependence allows the angular position of the leg with respect to the fixed axes to be calculated. If the start of the cycle of shank movement is chosen to occur during the 'foot-flat' period of the stance phase, the initial conditions needed to solve the simultaneous-differential equations for the instantaneous direction-cosine matrix are known. Figure 5 shows a display of the direction cosine matrix for a typical walking cycle.

With the solution for the direction cosine matrix available for each sample time, it is possible to solve for the translational components of the limb's movement. The angle which the axis of each transducer makes with the vertical is known, and the component of



a



b

Fig. 4a, b. A period of 2·56 sec of angular velocity data before and after filtering. The upper and lower traces in each picture show coronal and sagittal plane rotations, respectively.

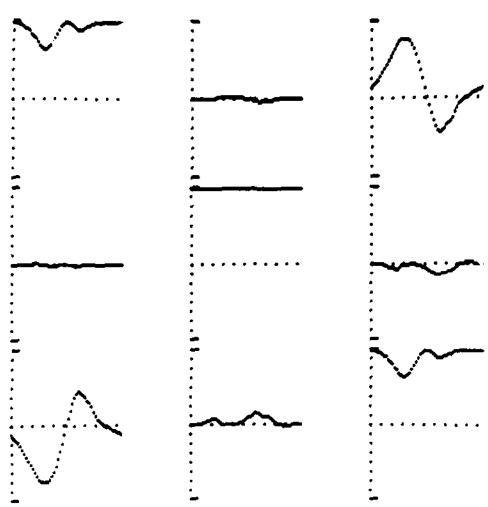


Fig. 5. The direction cosine matrix of the shank for one step, corresponding to time between the cursors in Figs. 4a and b.

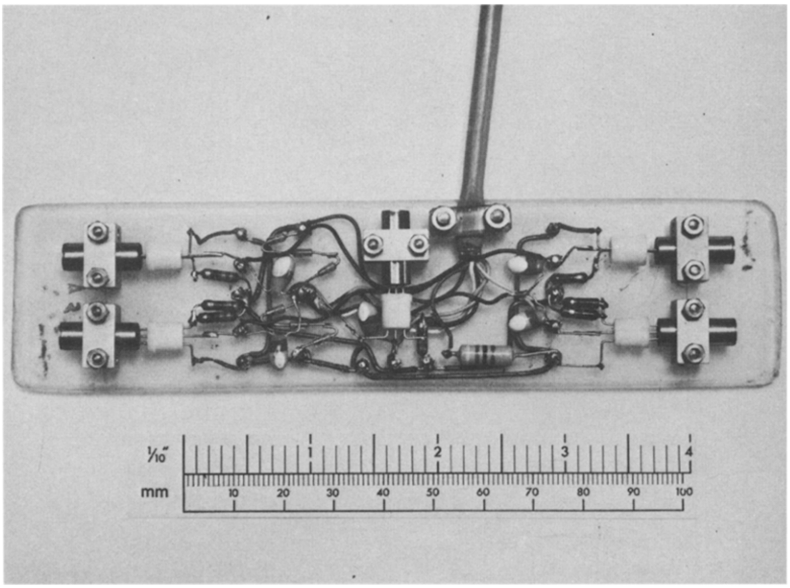


Fig. 3. The accelerometer mounting platform, showing five accelerometers and other associated electrical components.

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