MECHANICAL ANALYSIS OF THE STABILOGRAPHIC METHOD

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The stabilographic method is widely used to record movement of the center of gravity of the human body. However, mechanical analysis shows that many of the oscillations recorded in this way correspond to the acceleration and not the displacement of the center of gravity of the body. Simultaneous recording of the stabilogram and of acceleration of the center of gravity confirms the mechanical analysis.

The stabilographic method and others similar to it (statokinesimetry, stabilometry) are being increasingly used in laboratory investigations and in clinical practice. It is assumed that the position of the general center of gravity of the body (GCG) is recorded in this way. However, a detailed mechanical analysis shows that movement of the GCG is recorded with an error due to dynamic effects [1, 2].

There is thus a need for further detailed examination of the physical basis of these methods of recording so that precise technical instructions can be formulated on the method of handling the results.

EXPERIMENTAL METHOD

These methods are based on one general principle: the position of the point of application of the resultants of support reactions, taken as the position of the GCG, is determined from measurements of the vertical support reactions during standing by suitable commutation of the electric circuit. Without confining our attention to the general case, let us carry out a test calculation based on the use of the stabilograph. For the sake of simplicity and clarity let us assume that the human body can be approximated to a single-membered pendulum with an axis of rotation at the ankle, Let us also assume that the pendulum rests on an absolutely elastic stand which has contact with the platform of the stabilograph at only two points* (Fig. 1). The pendulum is stopped from falling by the stabilizing moment of the joint created by muscular action. Support reactions R_1 and R_2 as functions $\varphi(t)$ can be found for such a model.

EXPERIMENTAL RESULTS

For the position of the GCG the stabilograph gives the coordinate of the point of application of resultant support reactions R_1 and R_2:

$$x_1 = \frac{R_2 b - R_1 a}{R_1 + R_2}.$$

The true position of GCG is $x_c = -L \sin \varphi$.

The differences between the readings of the stabilograph and the position of GCG are given by

$$\delta = x_1 - x_c = L\,\frac{h(\ddot{\varphi}\cos\varphi - \dot{\varphi}^2 \sin\varphi) + L\ddot{\varphi} - L\ddot{\varphi}\sin^2\varphi - L\dot{\varphi}^2 \sin\varphi\cos\varphi}{g - L(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi)}.$$

Clearly when $\dot{\varphi} = \ddot{\varphi} = 0$, $\delta = 0$; i.e., the error is purely dynamic in origin.

The main term in the expression for the error given above is $(L^2/g)\ddot{\varphi}$. Let us now examine which oscillations of GCG the stabilogram reflects, and to what degree, i.e., for what types of $\varphi(t)\,\delta = 0$. Let us

*It is easy to show that the problem with an arbitrary distribution of reactions along the support can be reduced to such a situation.

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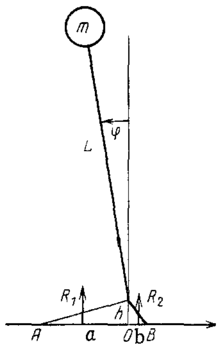

Fig. 1

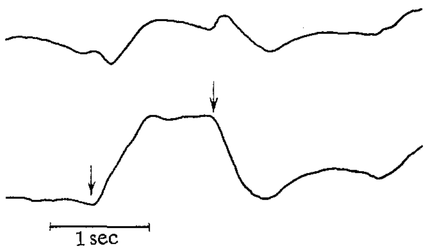

Fig. 2

Fig. 1. Single-membered model of the human body. Explanation in text.

Fig. 2. Sagittal stabilogram (above) and angle in ankle joint (below) during electrical stimulation of leg muscles. Arrows mark beginning and end of stimulation.

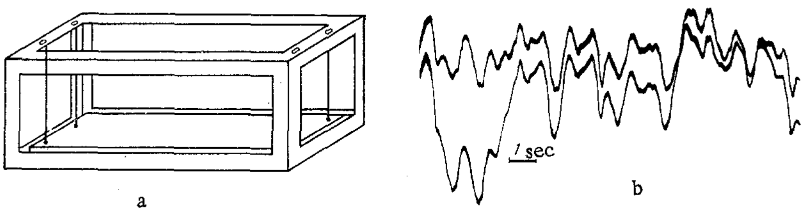

Fig. 3. Recording of acceleration of the general center of gravity of the body. a) Recording platform; b) acceleration of GCG (above) and sagittal stabilogram (below).

examine the following law of change $\varphi(t)$. $\varphi(t) = \varphi_0 + \varphi_1 \sin \omega t$, where φ_0 is the static angle and $\varphi_1 \sin \omega t$ applied oscillations of low amplitude. For such a frequency component the formula for the error becomes of the form: $\delta \sim (L^2/g)\varphi_1\omega^2$. The relative error is expressed as $(L/g)\omega^2$.

It follows from the last formula that when L = 1 m, g = 10 m/sec^2 and that the upper limit for the frequency of oscillations reflected with an error of not more than 10% is 0.2 Hz, while for oscillations with a frequency of 0.5 Hz the components of the stabilogram corresponding to displacement and acceleration are approximately equal.

It follows essentially from these calculations for an assumed single-membered model that the high-frequency components of the stabilograms (above 1 Hz) are due to acceleration of the GCG and not to its displacement and that, consequently, they correspond more to forces developed by the muscle. However, this main conclusion can be drawn from simple qualitative considerations. Let the force of the muscles change suddenly at a given moment of time, so that the body is subjected to acceleration directed backward. This can be produced by an increase in the level of activation of the gastrocnemius muscle. In that case the load on the posterior part of the foot is reduced, so that the load on the anterior part of the foot is increased. In that case the stabilogram will record "inclination forward," whereas the body is in fact being accelerated by the action of this force in the opposite direction. A similar picture will be found during activation of the tibialis anterior muscle.

The following experiment was carried out to verify these qualitative arguments. A change in the force of the leg muscles was produced by electrical stimulation in a person standing on the stabilograph. The sagittal stabilogram and the angle in the ankle joint were recorded. One such record is illustrated in Fig. 2. Clearly when the stimulus was applied the angle increased steadily in one direction. Meanwhile, the stabilogram responded to the beginning of stimulation by inclination in the opposite direction (acceleration), after which the displacement of the body was fixed. The same result was found in response to stimulation both of the gastrocnemius and of the tibialis anterior muscle. Although this test was artificial, the time characteristics (200-300 msec) show that the same picture is also observed during free standing.

The results described above and the theoretical conclusions show unequivocally that acceleration of the GCG makes a large contribution to the support reactions recorded on the stabilogram. To verify this hypothesis directly the following test was carried out. The sagittal stabilogram and the sagittal component of acceleration of the GCG were recorded simultaneously. To record acceleration of the whole body a method similar to that described by Thomas and Whitney [1] was used. The subject stood on the stabilograph on a platform suspended from a rigid frame by means of 4 steel wires. Lateral forces acting on such a system could be transmitted only through elastic rings by which the suspended platform was fixed to the same frame. External horizontal forces acting on the system man + stabilograph + platform could thus be recorded by means of strain gauges fixed to the elastic rings. In accordance with the well-known theorem in mechanics these forces were directly proportional to the corresponding components of acceleration of the center of gravity on the whole system (the coefficient of proportionality is the mass of the system). A general view of the platform for recording accelerations and a typical record are illustrated in Fig. 3. Slow oscillations of the stabilogram were hardly reflected at all on the acceleration curve, whereas the oscillations of higher frequency were well reflected. Close correlation between the waves can be seen up to frequencies of 0.3-0.5 Hz.

These results show that many of the waves in the stabilographic curves correspond to acceleration of the GCG and not to its displacement; i.e., they reflect stabilizing moments. As a result the high-frequency waves of the stabilogram (with a frequency of more than 1 Hz) must be regarded as a direct reflection of muscular activity on standing. It is therefore possible to estimate not only the "transgression of the control system" or quality of maintenance of the vertical posture, but also the work of the muscles required to do this. If for some reason or other it is desired to record the pure movement of the GCG, the acceleration must be integrated twice. To obtain a more exact approximation than the stabilogram, the component of the stabilogram corresponding to acceleration of the GCG can be compensated by suitable commutation of the electrical circuits of the stabilograph and platform for recording acceleration.

LITERATURE CITED

1. D. P. Thomas and R. J. Whitney, J. Anat. (London), 93, 524 (1959).
2. D. E. Scott and E. Dzendolet, Agressologie, 13, 35 (1972).