A model of the standing man for the description of his dynamic behaviour

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by

J.-B. GEURSEN *, D. ALTENA **, C.-H. MASSEN ***
and M. VERDUIN ****

* Epileptic Centre « Meer en Bosch », Heemstede,
** Department of Physics, University of Utrecht, Utrecht,
*** Department of Physics, Eindhoven University of Technology, Eindhoven,
and **** Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven.

A MODEL OF THE STANDING MAN FOR THE DESCRIPTION
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At preceding symposia it was explained how the static equilibrium position of the centre of mass of the human body can be determined. The mechanical moments which are evoked by the feet on the platform of a stabilometer, are measured for that determination.

This study has now been extended with the influence of the dynamic behaviour of the human body on such measurements. To this end a model of the human body is introduced with a view to describe the anterior-posterior movements. This model covers the assumption that the body consists of two parts, each represented by a reversed mathematical pendulum, the two pendula being of different lengths and having different masses. One pendulum is situated on top of the other, their connection is supposed to coincide with the hipjoint.

The study has led to the conclusion that body movements may lead to incorrect results concerning the horizontal displacements of the mass centre of gravity of the human body.

The actual displacements may be much smaller than those deduced by means of a « static » interpretation of the measured mechanical moments.

Introduction.

The movements of the human body during standing have been subjected to study by many investigators (THOMAS and WHITNEY, 1959 ; NJIOKIKTJIEN, 1971 ; KAPTEYN, 1973 ; O'CONNEL and GARDNER, 1972; SCOTT and DZENDOLETT, 1972). In recent years techniques have been developed to measure these movements. In one of these techniques use is made of a platform on which the patient is standing. Underneath the platform a number of force-transducers measure vertical forces. The signal from the force transducers is often used for additional electronic computing. In case one wants to register, as in stabilometry, the position of the vertical projection of the mass centre of gravity, the computations are adapted to this end. From a recording (as a function of time), one is often inclined to conclude that it indeed represents the horizontal movement of the mass centre of gravity. This would be correct if the whole system of platform and patient were in static equilibrium at every time. In fact, however, the recordings shows fluctuations within short time intervals. These fluctuations are partly caused by movements of the mass centre of gravity and partly a result of accelerations.

In the present paper a double compound pendulum will serve as a model of the human body for estimating the influence of such accelerations on a stabilographic recording. With the help of an experimental model, stabilographic recordings are compared with theory.

Theory.

The theoretical treatment will be based on the reversed double pendulum (Fig. 1), the two parts each being a compound pendulum ; this model is a generalization of the GURFINKEL model (GURFINKEL, 1973). A compound pendulum is an arbitrary rigid body pivoted upon a horizontal axis, and moving under gravity. We assume the horizontal axis 0 of the lower pendulum to coincide with the rotation axis of the ankle joint, the axis 0' of the higher one to coincide with the rotation axis of the hip joint. The head is supposed to have a fixed position with respect to the thorax and the knee joint is supposed to be « locked » (NJIOKIKTJIEN, 1971).

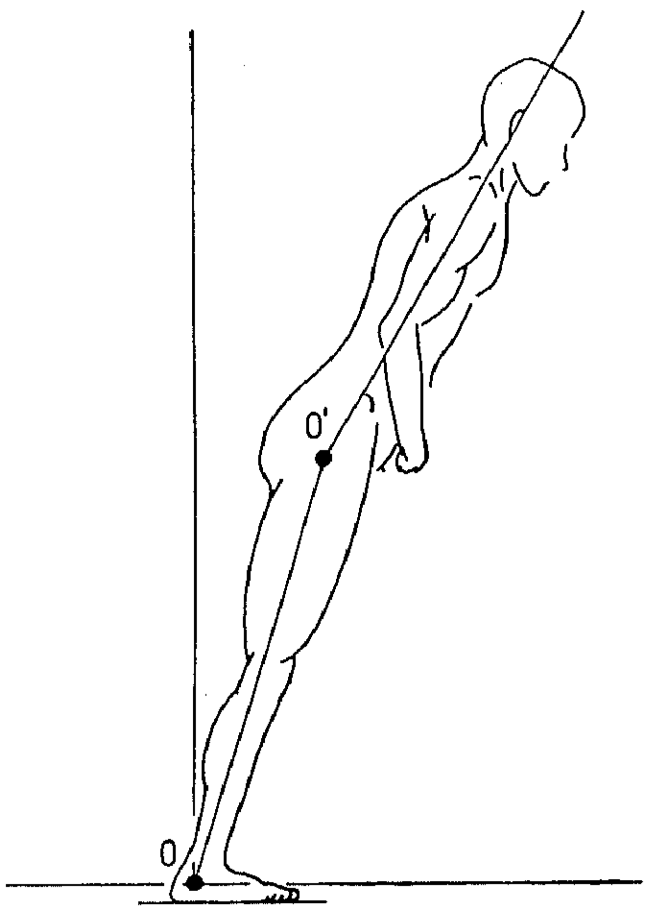

FIGURE 1. — The human body in an exagerated anterior position. 0 and 0' indicate the rotation axes of the two body segments each being a compound pendulum.

From mechanics one can prove that the dynamic behaviour of a compound pendulum can be described with the help of a simple pendulum. A simple pendulum consists of a weightless rod, with at one end a pointmass and with the rotation axis, perpendicular to the rod, through the other end. The use of a simple pendulum instead of a compound one needs only a mathematic conversion and will simplify the further calculations to calculations in terms of two simple pendula. In our case we choose the masses m_1 and m_2 of each of the pendula to be at a distance r_1 and r_2 from their rotation axes 0 and 0' respectively. The distance between the two rotation axes is l. For the description of the movements we take then angles θ_1 and θ_2 as drawn in Fig. 2. There will be a mechanical

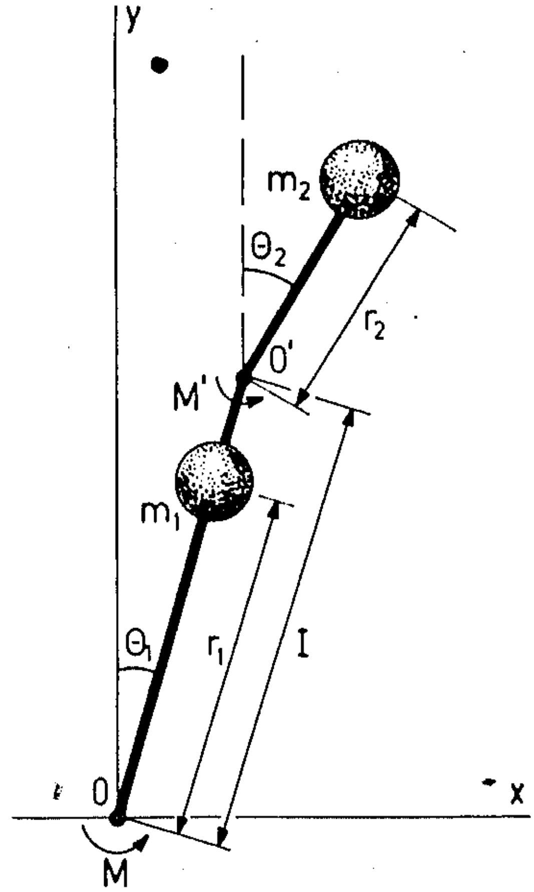

FIGURE 2. — The two simple pendula.

moment M around axis 0 and a moment M' around axis 0'. From the equation of motion of the reversed double pendulum (GEURSEN, 1975), it follows :

$$M = m_1 r_1^2 \ddot{\theta}_1 + m_2 \ell^2 \ddot{\theta}_1 + m_2 \ell r_2 (\ddot{\theta}_1 + \ddot{\theta}_2)\cos(\theta_1 - \theta_2) - m_2 \ell r_2 (\dot{\theta}_1^2 - \dot{\theta}_2^2)\sin(\theta_1 - \theta_2) +$$
$$+ m_2 r_2^2 \ddot{\theta}_2 - m_2 g r_2 \sin\theta_2 - (m_1 g r_1 + m_2 g \ell)\sin\theta_1 \qquad (1)$$

where θ'_1 and θ'_2, and θ''_1 and θ''_2 are the first and second derivative with respect to time of θ_1 and θ_2 respectively and g is the acceleration due to gravity. (1) is laborious to use, therefore we will simplify it. To this end we will estimate the relative importance of the different terms to find out if neglection of one or more terms is allowed. In order to get an impression of the magnitude of θ_1 and θ_2 measurements have been carried out on testpersons. The amplitudes of the upper and the lower part of the body were measured from which θ_1 and θ_2 have been calculated (GEURSEN and ALTENA, 1974). To get useful information the testpersons were asked to make swaying movements, because in this case their movements appeared to be closest to harmonic ones, so that θ'_1, θ'_1, θ''_2 and θ''_2 can be determined more easily. These measurements showed that θ_1 and θ_2 were small enough to allow for the approximations :

$$\sin\theta_1 = \theta_1, \quad \sin\theta_2 = \theta_2, \quad \cos\theta_1 = 1 \quad \text{and} \quad \cos\theta_2 = 1 \qquad (2)$$

With the help of literature (O'CONNEL and GARDNER, 1972) an estimate could be made of m_1, m_2, r_1, r_2 and l. From the results one can calculate that in the RHS of (1) the fourth term may be neglected, so we may write :

$$M = (m_1 r_1^2 + m_2 \ell^2 + m_2 \ell r_2)\ddot{\theta}_1 + (m_2 r_2^2 + m_2 r_2 \ell) f \ddot{\theta}_1 -$$
$$- (m_1 g r_1 + m_2 g \ell)\theta_1 - m_2 g r_2 f \theta_1 . \qquad (3)$$

This expression is easier to handle. Once M is measured and m_1, m_2, r_1, r_2 and l are known, one can consider (3) as a relation between θ_1 and θ_2. In order to find the position of the mass centre of gravity from a measurement of M one needs in addition a measurement of either θ_1 or θ_2.

From the measurements on the amplitude of the movements of test persons (GEURSEN and ALTENA, 1974) we make use of the result that both the frequency and the fase of the lower and higher body segments are the same (see also VALK-FAI, 1973). The above result can be expressed in the relation :

$$\theta_2 = f\theta_1 \qquad (4)$$

where $f > 0$.

Introducing (4) into (3) yields :

$$M = (m_1 r_1^2 + m_2 \ell^2 + m_2 \ell r_2)\ddot{\theta}_1 + (m_2 r_2^2 + m_2 r_2 \ell)\ddot{\theta}_2 -$$
$$- (m_1 g r_1 + m_2 g \ell)\theta_1 - m_2 g r_2 \theta_2 \qquad (5)$$

For the position x_c of the mass centre of gravity and the acceleration x''_c of the total mass m_t ($= m_1 + m_2$), we can write :

$$m_t x_c = (m_1 r_1 + m_2 \ell)\theta_1 + m_2 r_2 \theta_2 \qquad (6)$$

and

$$m_t \ddot{x}_c = (m_1 r_1 + m_2 \ell)\ddot{\theta}_1 + m_2 r_2 \ddot{\theta}_2 , \qquad (7)$$

where the approximations of (2) are incorporated. With the help of (4), (6) and (7) can be written as :

$$m_t \ddot{x}_c = [m_1 r_1 + m_2(\ell + r_2 f)]\ddot{\theta}_1 . \qquad (8)$$

$$m_t x_c = [m_1 r_1 + m_2(\ell + r_2 f)]\theta_1 \qquad (9)$$

Solving θ_1 and θ''_1 from (8) and (9) and substituting θ_1 and θ''_1 in (5) yields :

$$M = -m_t g x_c + m_t \ddot{x}_c L \qquad (10)$$

where L satisfies :

$$L = \frac{(\ell + r_2 f)(\ell + r_2) + \frac{m_1}{m_2} r_1^2}{\ell + r_2 f + \frac{m_1}{m_2} r_1} \qquad (11)$$

Note that (10) describes the moment of one simple pendulum of length L and mass m, which expresses the fact that the double compound pendulum is reduced to one simple one (Fig. 3). In Fig. 4 the dependence of L upon f and the influence of model parameters on it, is illustrated. It appears that upon variation of either m_1 or m_2 or r_1 or r_2 within some 20 per cent. and for values of f between 0.3 and 1.0 the magnitude of L varies only a few per cent. Variation of l has the most important influence on the value of L, but l can be determined, with sufficient exactitude, for every person.

Further investigations have to be done with respect to the mass distribution in vertical direction for the determination of the values of m_1, m_2, r_1 and r_2.

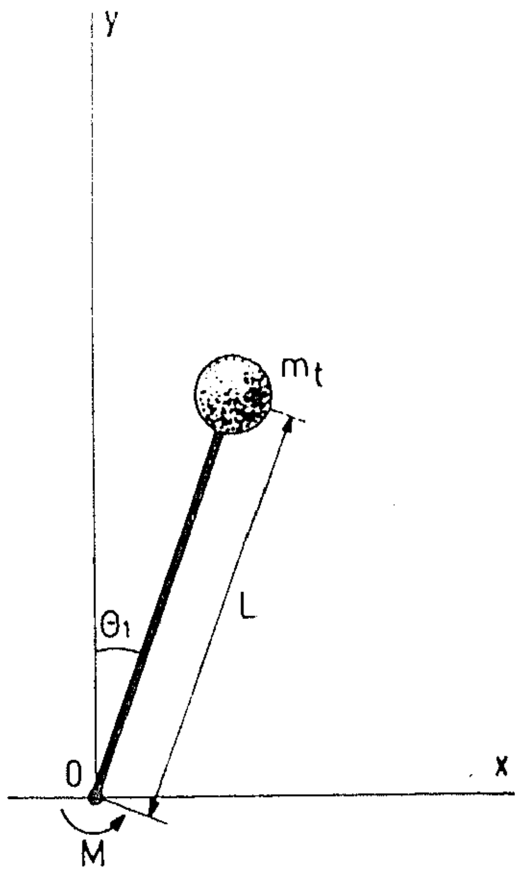

FIGURE 3. — The (ultimate) simple pendulum.

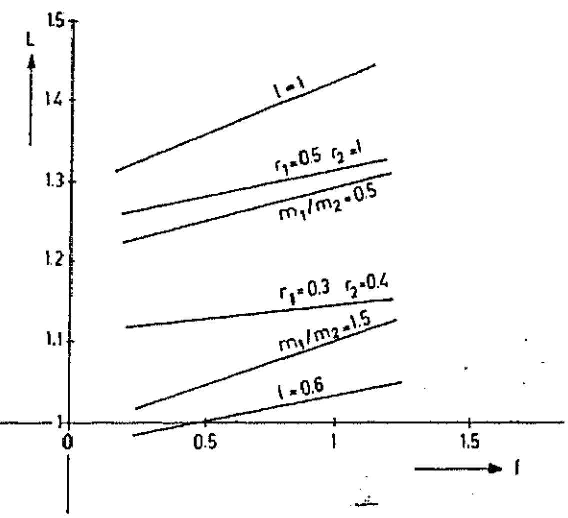

FIGURE 3. — The dependence of the length L of the ultimate simple pendulum on the quantity f, for different values of the parameters m_1/m_2, r_1, r_2 and l. If parameter values are not quoted their values are $m_1/m_2 = 5/6$, $r_1 = 0.4$ m, $r_2 = 0.6$ m and $l = 0.8$ m.

With (10) it is possible to deduce the position of the mass centre of gravity once M and the frequency of oscillation are measured.

Experimental.

In order to verify the above theoretical results experiments have been set up where the human body is represented by a reversed pendulum (Fig. 5).

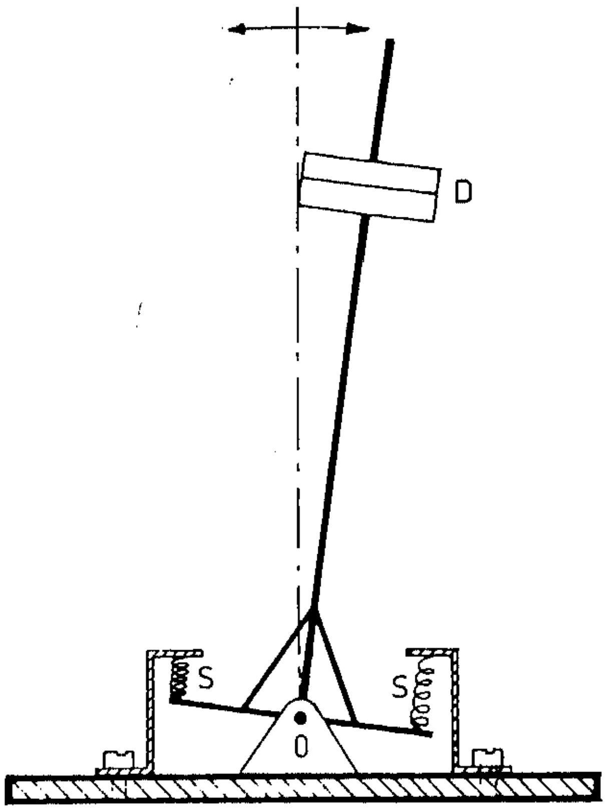

FIGURE 5. — A schematic representation of the reversed pendulum as used in the experiments. O the rotation axis ; S spring ; D lead disks representing the total mass m_{tot}.

This pendulum has been placed on a platform of a stabilograph and stabilograms have been made under different circumstances. In Fig. 6 such a stabilogram is presented. The measurement procedure was as follows :

I. - The model is in its equilibrium position (vertical), A in Fig. 6.

II. - The model is forced in an out of equilibrium position by means of a thread between pendulum and platform. Now the position of the centre of gravity is changed, B in Fig. 6.

III. - The thread is cut and the pendulum sways with the amplitude given at II.

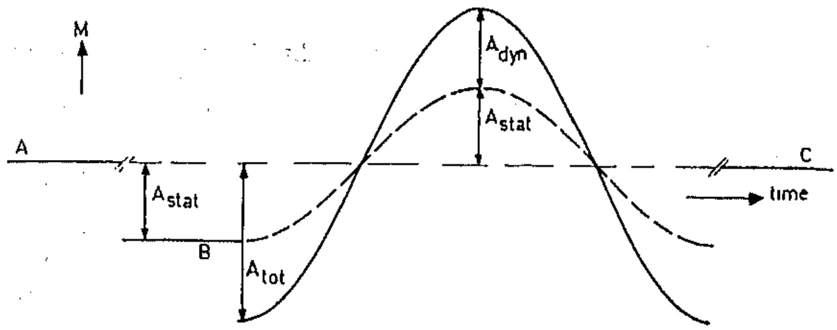

FIGURE 6. — The mechanical moment as a function of time in the course of an experiment. Between B and C the full curve represents the measured mechanical moment (one sway) with amplitude A_{tot}, here the dotted line represents the static part of the measured mechanical moment, its amplitude A_{stat} being equal to the measured mechanical moment at B.

IV. - The pendulum is stopped to control the equilibrium position of I., C in Fig. 6.

From Fig. 6 it is clear that the dynamic character of the movement may become very important. We see in this example that the amplitude of M measured during the harmonic motion, is approximately two times the value of M which was given as the initial static moment.

The theory (10) in this case, where harmonic movements of frequency ν are considered, yields a simple expression for the measured amplitudes A_{tot} of M :

$$A_{tot} = m_t g x_c + 4\pi^2 m_t L x_c \nu^2 \qquad (12)$$

where x_c is the amplitude of the movements of m_t. For very low frequencies, quasi-static conditions, the second term in the RMS of (12) is negligeable, so that than from A_{tot} indeed the value of x_c can be obtained (SNIJDERS and VERDUIN, 1973 ; VERDUIN and SNIJDERS, 1974). The experimental results are presented in Fig. 7 where $\frac{A_{tot}}{A_{stat}}$ is plotted as a function of ν being the frequency of the freely swaying reversed pendulum, ν is altered by using different sets of springs (Fig. 5). In Fig. 7 A_{stat} stands for the measured static moment (B in Fig. 6) so the influence of the movement is to be found in the difference of $\frac{A_{tot}}{A_{stat}}$ from one. Working out this yields :

$$\frac{A_{tot}}{A_{stat}} - 1 = \frac{A_{tot} - A_{stat}}{A_{stat}} = \frac{A_{dyn}}{A_{stat}} \, . \qquad (13)$$

In Fig. 8 $\frac{A_{dyn}}{A_{stat}}$ is plotted as a function of ω^2

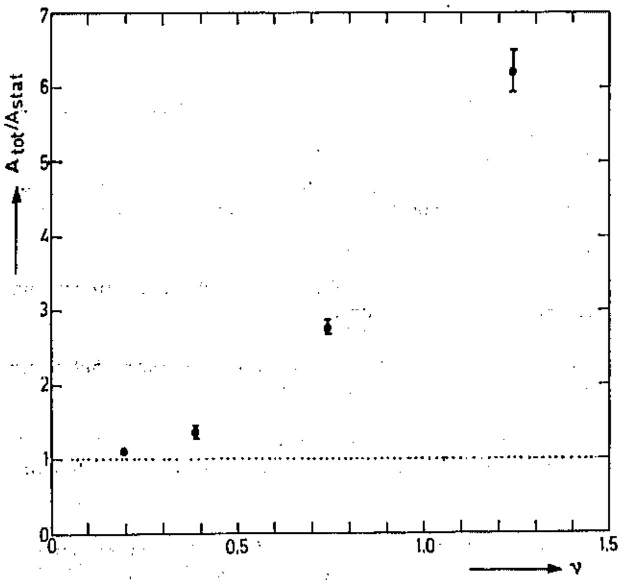

FIGURE 7. — The measured values of $\frac{A_{tot}}{A_{stat}}$ as a function of the frequency ν.

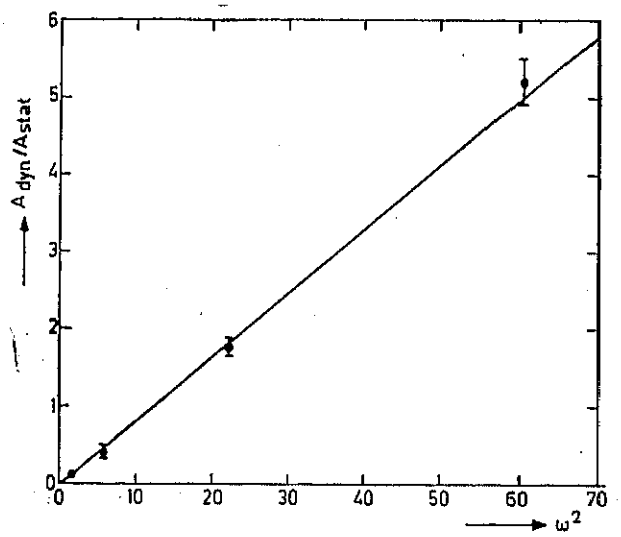

FIGURE 8. — The dots represent the values of $\frac{A_{dyn}}{A_{stat}}$ as determined from the measurements. The line drawn is obtained from eqns. (12) and (13).

where $\omega = 2\pi\nu$. From (12) and (13) it follows that $\frac{A_{dyn}}{A_{stat}}$ should be proportional with ν^2 and so with ω^2. This proportionality is presented by the line drawn.

Discussion.

The theory is based on the model of the reversed double compound pendulum. In reality one has to take into account also the position of the ankle joint with respect to the platform and in particular to the position of the force transducers (MASSEN, BREAS *et al.*, 1976). The model chosen is in particular suitable for describing posterior-anterior body movements, additional study is necessary to investigate the applicability of our model to lateral movements.

In order to be able to calculate from the measured values of A_{tot} the displacement of the mass centre of gravity of the body it is necessary to have at the disposal information on the actual mass distribution along the body and of the frequency of movement. For the same reason one has to know the exact positions of the two rotation axes.

The influence of the dynamic character of standing having such great consequences for the determination of x_c it becomes also important to know the frequency response of the whole stabilographic equipment (VERDUIN, BREAS *et al.*, 1976).

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Reprints : Ir. L. KODDE
Department of Mechanical Engineering
Eindhoven University of Technology
P.O. Box 513
Eindhoven, the Netherlands.

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RÉSUMÉ

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Modèle de l'homme debout
pour la description de son comportement dynamique.

Il avait été expliqué aux précédents symposia comment la position d'équilibre statique du centre de la masse corporelle humaine peut être détournée. Ce sont les moments mécaniques évoqués par les pieds sur la plateforme d'un stabilomètre qui sont mesurés pour cette détermination.

L'étude actuelle a été étendue à l'influence du comportement dynamique du corps humain sur une telle mesure. Il est fait appel à un modèle du corps humain pour décrire les mouvements antéro-postérieurs, modèle qui part de l'hypothèse que le corps est fait de deux segments chacun représenté par un pendule mathématique renversé, les deux pendules étant de longueur et possédant des masses différentes. Ils sont situés l'un au-dessus de l'autre, leur articulation étant supposée coïncider avec la hanche.

L'étude conduit à la conclusion que les mouvements corporels risquent de fausser l'interprétation des mouvements horizontaux du centre de gravité de la masse corporelle humaine.

Les déplacements réels peuvent être plus petits que ceux déduits par l'interprétation « statique » des moments mécaniques mesurés.