A MODEL OF HUMAN POSTURE CONTROL SYSTEM

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Summary

The prerequisite for constructing an automotive biped walking machine is to ensure the maintenance of the whole system at a stable, erect position. By way of preparation for such a machine, an attempt was made to make up a model of the function of the human body to maintain its equilibrium. This system is composed of two rigid levers, upper and lower, which represent the trunk and the lower limbs of man, respectively.

The driving device consists of artificial muscles made of rubber, which correspond in their funtions with major driving muscles and antagonistic muscles. As analogous to the reciprocal motion of groups of skeletal muscles, this model is provided with a clutch mechanism using rubber artificial muscles. Equilibrium of this system is maintained as follows. The lever deflection angle is detected by means of a potentiometer attached on the rotary shaft, and the deflection voltage drives the solenoid valve via a compensating circuit, with the result that the rubber artificial muscles repeat reciprocal action, holding the lever at a prescribed position.

Introduction

Man is a biped. It is said that the biped walking mechanism, erect posture, and the accompanying physiological development of the brains have helped the human being to acquire characteristics that clearly distinguish him from other animals. On the basis of the recent development in control engineering, attempts are being made in varied fields to realize mechanical models which correspond to the human leg, and the objectives of these investigations are to create an anthropomorphic locomotor robot in industrial applications and lower limb prostheses for medical purposes.

The biped locomotion necessitates an unstable condition in the act of moving, for one foot has to sustain the total weight of the body, including that of the other leg, at a certain phase of locomotion. Therefore, if it is intended to construct a biped walking machine that is selfpowered, it is essential that a stable and erect state of the entire system be maintained.

The research reported in this paper deals with an attempt at making a mechanical model incorporating the biped walking mechanism by maintaining the balance of his erect posture, as a preliminary step for studying the more intricate functions of human biped locomotion. As may be readily imagined, this is intrinsically an unstable mechanical system, and its stabilization is characteristically comparable to that of an inverted pendulum. Here arise two major problems to be solved. The first is the problem of the actuator. The human is actuated by soft and light-weight skeletal muscles which can put forth, in an efficient manner, enough power to keep the body balanced. By comparison, a series of conventional industrial actuators, typified by an electric motor, are heavy in themselves in comparison with the power generated. If such an industrial actuator is installed in the same position as living muscles, the instability of a resultant model would be so high that controlling is out of the question. For this reason, artificial rubber-muscles were adopted for the author's trial model as rubber provides a light-weight actuator. The second problem consists in how to develop an optimum system in which a highly unstable object can be controlled. It is obvious that the control device requires a precise knowledge of the condition of the object to be controlled, and a prompt information processing. Figure 1 illustrates the essential problems concerning the movement of a locomotor

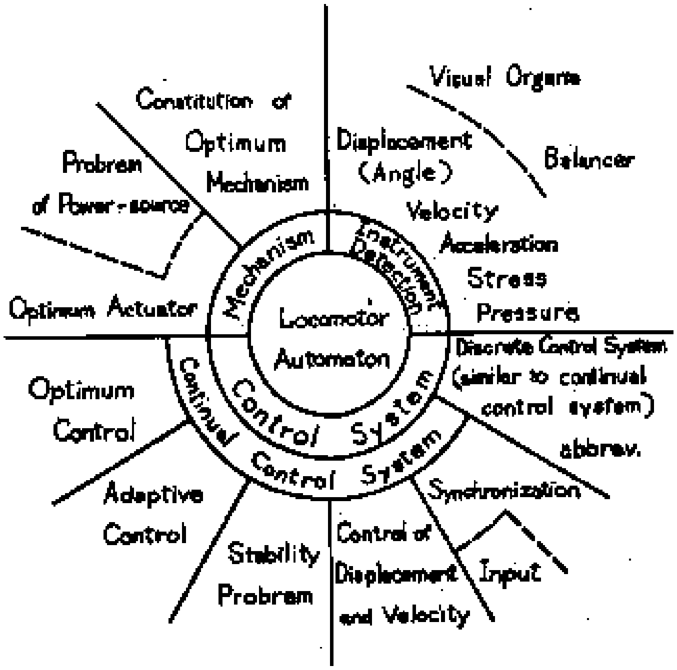


Fig. 1. Essential problems concerning the movement of a locomotor automaton.

automaton, and it is clearly indicated that the control system constitutes a focal point of all considerations. Therefore, in the beginning of this research, the balancing function of the human being was studied from the biological viewpoint in connection with the structure of the control device, and the characteristics of the balancing function of the human being were determined on the basis of tests on human functions to secure balance of the body. These findings were subsequently utilized for the construction of a mechanical mode of the analogy of the human control mechanism from a control engineering standpoint. Incidentally, these experiments also yielded some results of significance in terms of ergonomics.

Experiments on the Characteristics of the Balancing Function of the Human Being

The self-balancing function of the human being is to be studied with special emphasis laid on the back-and-forth and right-and-left motions of the trunk. The question is which frequency command variation the human body is able to follow while maintaining its balance, and what kind of compensatory action the human body performs technologically to support its erect posture.

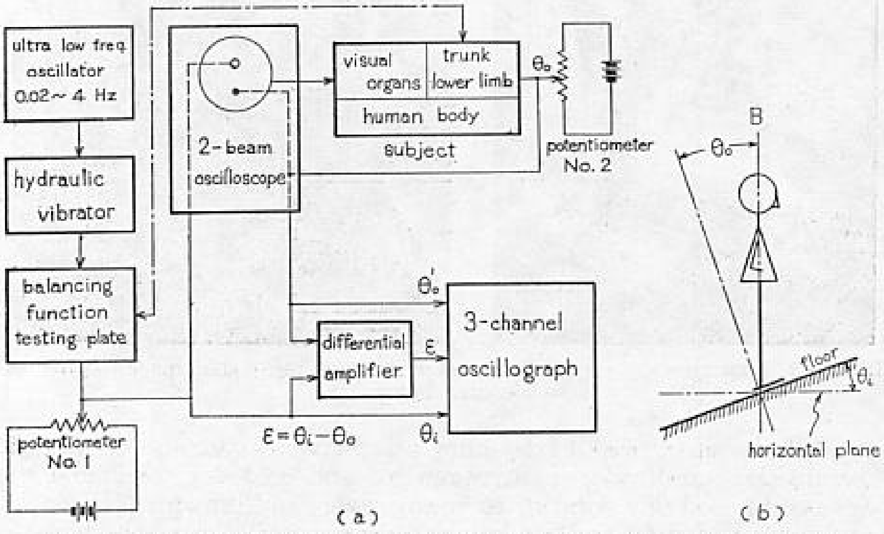


Fig. 2. Constitution of the experimental system: (a) block diagram (b) definition of θ_0 and θ_i.

In order to clarify the above points, the following experiment was conducted to measure the balancing function of the human being. The experimental system was, as illustrated in Figure 2, an arrangement including the two-beam oscilloscope designed for imparting precision visual feedback information to the subject. The subject was ordered to maintain balance only by the motion centered around the ankle with his arms stuck on both sides and his trunk kept immovable to deprive the upper body and knees of motion. For a device to give an input angle to the human body, a balancing function testing plate was designed. The purpose of this plate is to provide input for the examination of the body's balancing function by making a human being stand upright on the plate, which was moved like a seesaw so as to form a sine wave. The device was driven by a hydraulic vibration testing machine. The vertical stroke of this vibrator was converted into the change of rotary angle by means of a link mechanism. Photo 1 illustrates how the experiment was carried out.

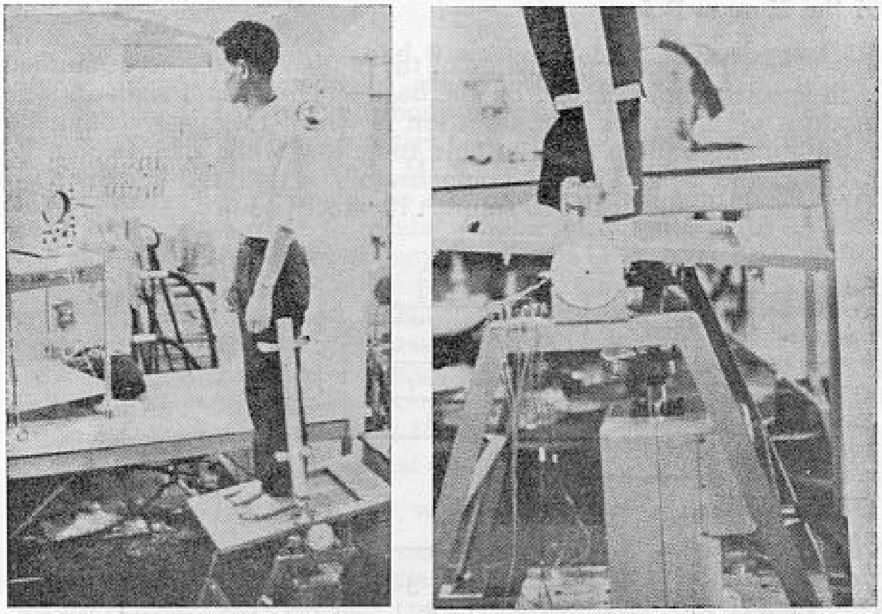


Photo. 1. Experiments on the characteristics of the balancing function of human being.

The working input frequency was between 0.02 and 2 Hz. and the angular amplitude was between ±5 and ±15 deg. The subjects were composed of a total of 16 young males and females. The back-and-forth and right-and-left balancing characteristics of the human body were measured, with the legs put together, while the eyes were opened and closed. Moreover, the opened eye characteristics were further divided between the case in which precision visual feedback was used and the case in which ordinary visual feedback was used by using and not using the oscilloscope. In the former case, the command spot and the spot tracking on the cathode-ray tube were respectively located by the uotput voltage of the potentiometer installed on the axis of rotation of the balancing function testing plate, and by the output voltage of the potentiometer provided at the ankle for detection of the inclination of the trunk. When the upright posture was held, the two bright spots overlapped each other. After allowing the subject to practice tracking the target for about three minutes, the characteristic was determined. The results will be described in the next section.

Deviation Wave-Form Group

Figure 3 illustrates an example of deviation waveform at each driving frequency of the balancing function testing plate. The figure disclosed the fact that the tracking performance concerning human balancing function has three different patterns depending upon the frequency range, as follows:

a) Saw-tooth wave-form group:
 0 — 0.1 Hz. (Group I in Figure 3)

b) Relatively gentle wave-form group-the fundamental wave is not predominant:
 0.2 — 0.8 Hz (Group II in Figure 3)

c) Wave-form group centered around the fundamental wave:
 1.0 — 2.0 Hz (Group III in Figure 3)

It is thus known that in the range of (a), the human being reacts to the integration of the variation. In other words, it is assumed that when the variation is integrated up to the level of sensory threshold and the integral value of the angle reaches the same level, the action of correction is started. In Figure 4 is plotted the frequency of the occurrence of saw-tooth waves. The frequency of occurrence is defined by the inverse number of the interval τ (s) of occurrence of saw-tooth waves. As the result, and for reasons mentioned earlier, the waves occur more frequently where the variation is larger, that is, velocity input is greater, while the increase and decrease of the frequency of occurence take place at the same periodicity as the input. In case precision visual information is provided, the saw-tooth waves occur more frequently when the testing plate moves from its forward position through the horizontal state to its backward position. One of the reasons may be found in the human's instinctive aversion to the backward inclination of the body owing to his physical structure. When visual information is absent, the occurrence is characteristically frequent during forward inclination, too. Range (b) is most favorable to the subject, who can easily and smoothly follow the variation with minimal fatigue.

so that sensitive response is possible against the input velocity. In range (c), the subject is not very much fatigued, but he is prevented from performing precise tracking action. Thus he is forced to keep a proper timing of the motion to follow the target. Accordingly,

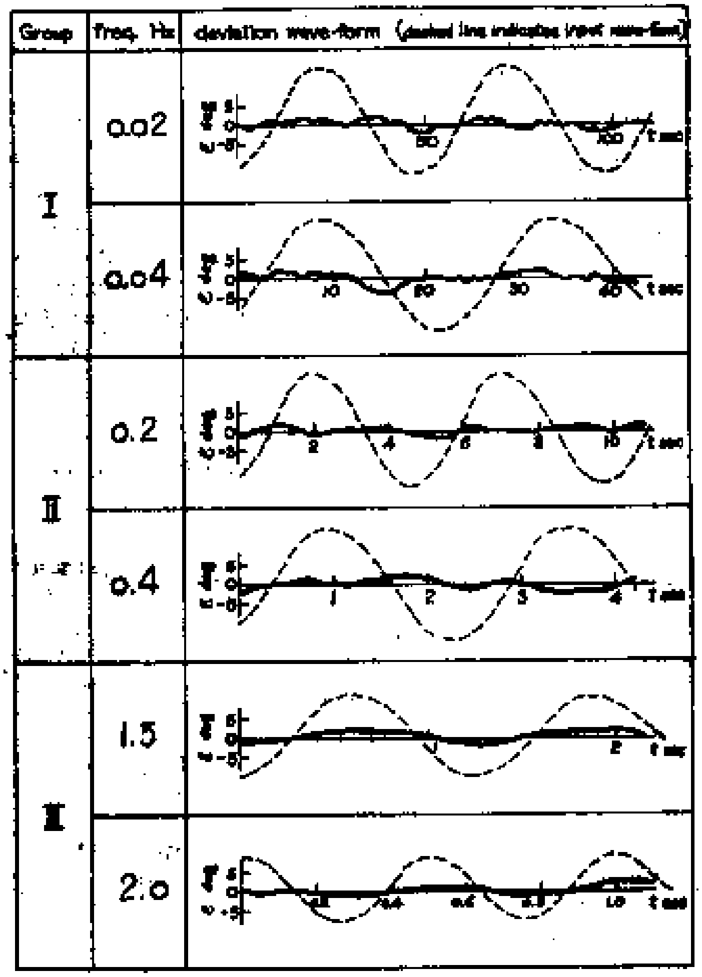


Fig. 3. Deviation wave-form under the precision visual information.

this is the limit for adequate tracking. In particular, the upper limit of this range involves a case in which good timing can be kept depending upon the cycle peculiar to the subject, and another case in which the subject cannot get back phase difference due to the delay of a definite cycle.

Deviation

Figure 5 shows the frequency characteristic of mean deviation in the balancing function. The mean deviation is obtained by averaging the same number of samples from the deviation waveform of a definite periodicity. From Figure 5, we can define how the mean deviation E is affected by the presence or absence of visual feedback. Up to 0.4 Hz, as may be easily anticipated, the deviation when the eye is closed is greater than that in opened eye. Beyond that, deviation on the whole tends to decline, while conversely within the timing range there is a tendency that deviation is smaller in closed eye than opened eye. This indicates that in the range mentioned above, better tracking can be performed in closed eye

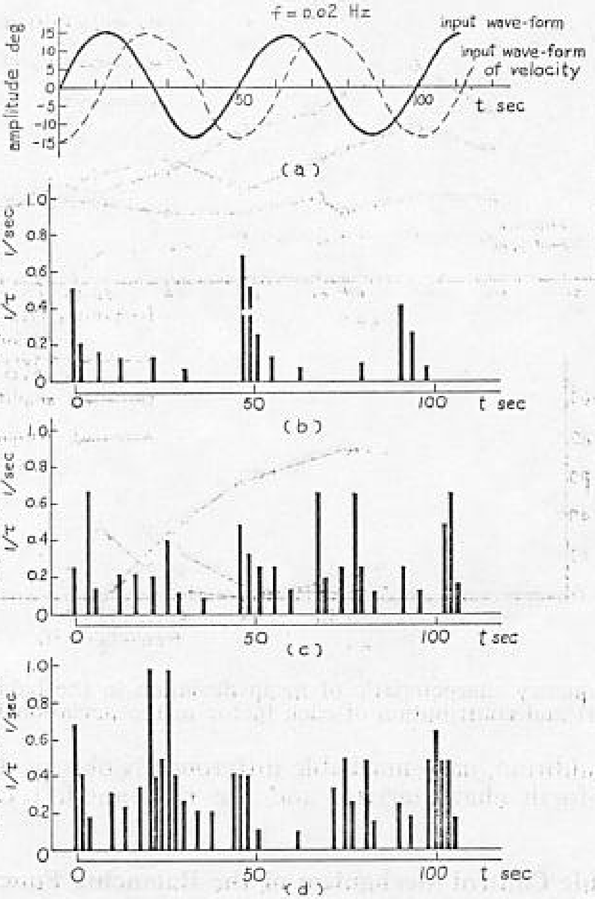


Fig. 4. Frequency of occurrence of saw- tooth waves: (a) input wave-form; (b) F.V.O. characteristics; (c) F.V. characteristics; (d) F.C. characteristics.

when visual information is suspended. This is an interesting example showing the case of excessive input information. Figure 5 meanwhile shows the contribution of each factor to the deviation. It is thus possible to know quantitatively which factor produces effect on the deviation.

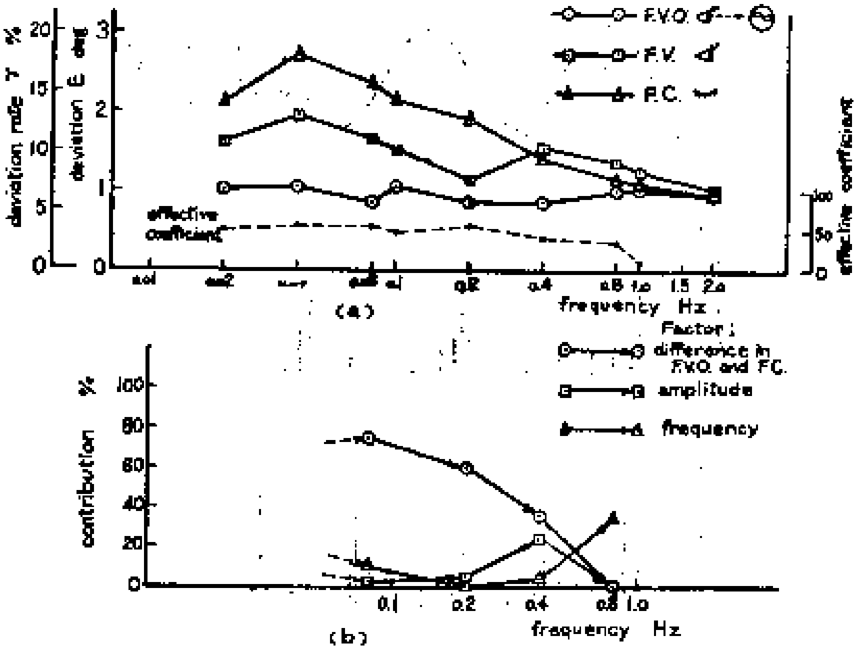


Fig. 5. Frequency characteristic of mean deviation in the balancing function (a) and contribution of each factor to the deviation E (b).

In addition, no remarkable difference is observed between the back-and-forth characteristic and the right-and-left characteristic.

Presumable Control Mechanism of the Balancing Function of Human Being

The following are considered to be the major factors responsible for controlling the balance of the human body:

a) Feedback information through the eye and ear
b) Feedback information through the balance detecting organ like the three semicircular canals
c) Feedback information from the muscles spindles, tendon spindles, and the like.
d) Feedback information due to the sensitivity to pressure at the tip of the foot and the like

It is not hand to imagine that a multiloop is formed by such factors interacting on one another. It is assumed, however, that the entire mechanism is represented by an all-inclusive unity feedback control system illustrated in Figure 6. The transfer function of the sensory system is represented by

$$G_1(s)=1.$$

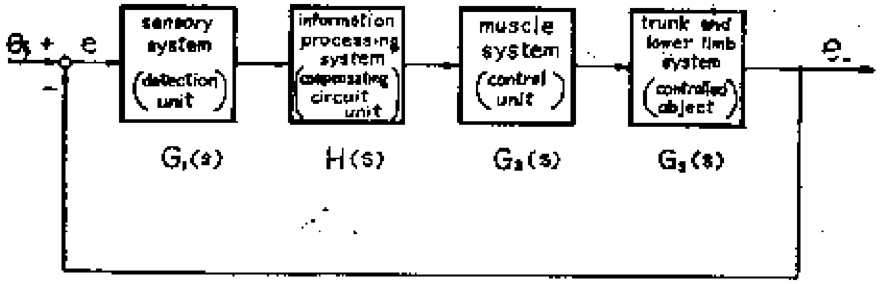


Fig. 6. Block diagram of the balancing system of human being.

And the muscular system is regarded approximately as a linear system expressed by the following equation:

$$G_2(s)=\frac{K_1}{1+T_2\, s}$$

As for the transfer function $G_3(s)$ for the trunk and lower limb system, the human body is regarded as a single rigid bar like an inverted pendulum, as in the test for the balancing function (Section 2 above), and the behavior of the assumed bar is analyzed.

In Figure 7, assuming the input angle to be denoted by θ_i [rad] and the amplitude of the rigid lever from the vertical line by θ [rad], we obtain

$$(I+ma^2)\,\ddot{\theta}-mg\,a\sin\theta=M$$

In the vicinity of the erect posture in which θ_i+0, we have $\sin\theta\fallingdotseq\theta$.

The assuming $\alpha_1=I+ma^2$ and $\alpha_2=mg\,a$, we can define $G_3(s)$ as follows:

$$G_3(s)=\frac{1}{\alpha_1 s^2-\alpha_2}$$

And yet the compensating network H (s) is not defined. Substituting the above results into the system given in Figure 6, the closed loop transfer function W (s) of the system is determined as follows:

$$W(s)=\frac{H(s)\dfrac{K_1}{T_1s+1}\,\dfrac{1}{\alpha_1s^2-\alpha_2}}{1+H(s)\dfrac{K_1}{T_1s+1}\,\dfrac{1}{\alpha_1s^2-\alpha_2}}$$

Hence the characteristic equation is written as follows:

$$\alpha_1T_1s^3+\alpha_1s^2-\alpha_2T_1s-\alpha_2+KH(s)=0 \tag{1}$$

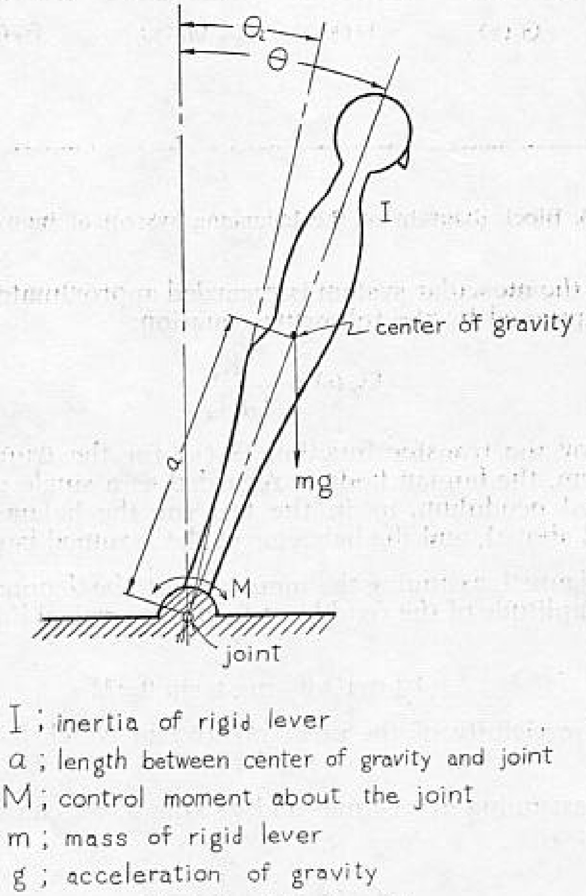


Fig. 7. Analytical model.

Inasmuch as the human being can maintain its erect posture adequately despite more or less disturbance from outside the system involved must be stable within limited angles. For this reason, we are justified to consider H(s) which may be called a unit for information processing on the basis of the procedure for assessing the stability of the control system.

The necessary condition for the root of the characteristic equation (1) to exist on the left half of the root plane is "to have all coefficients of the characteristic equation present and that they should be of the same sign". In Eq. (1), it is assumed that the physical realization of a model construction is high, and that the compensating factors have the smallest possible value of s. Then since K_1, T_1 α_1 and α_2 are positive, it is necessary that the following equation should hold true in order that the term of $K_1H(s)$ may at least efface the term of $(-\alpha_2T_1s-\alpha_2)$, while the characteristic equation possesses a positive linear term of s and a constant term.

$$H(s)=K_2(T_2s+1) \tag{2}$$

Substituting Eq. (2) into Eq. (1), we have

$$\alpha_1T_1s^3+\alpha_1s^2+(K_1K_2T_2-\alpha_2T_1)s+(K_1K_2-\alpha_2)=0 \tag{3}$$

In the next place, the problem will be considered from the Hurwitz's conditions. Hurwitz's determinant is as follows:

$$\Delta_1=\ \alpha_1>0$$

$$\Delta_2=\begin{vmatrix}\alpha_1 & K_1K_2-\alpha_2\\ \alpha_1T_1 & K_1K_2-\alpha_2T_1\end{vmatrix}$$

$$=\alpha_1K_1K_2(T_2-T_1)$$

Therefore, in order that this control system may be stable, the compensating circuit H(s) must at least meet the following conditions:

$$H(s)=K_2(T_2s+1)$$

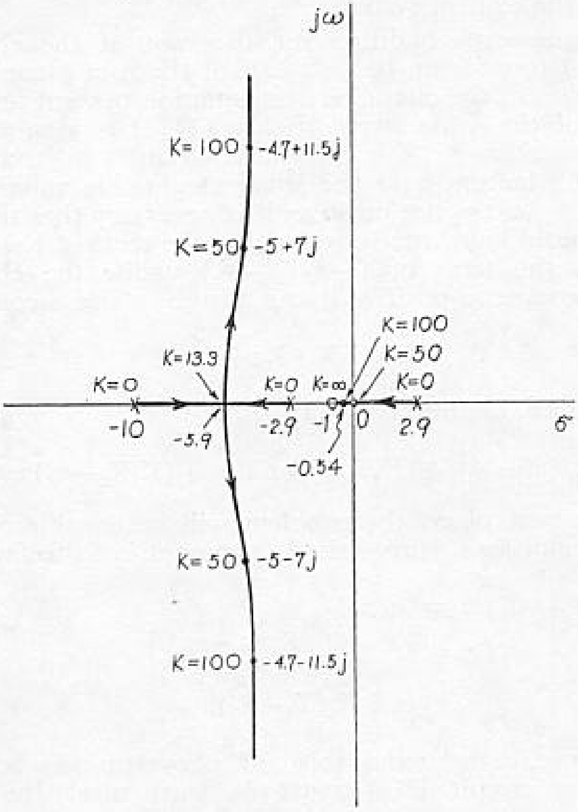
$$\text{and } K_1K_2>\alpha_2,\ T_2>T_1 \tag{4}$$

Assuming a typical human body with a weight of mg=60 kg and a stature L=1.7 m, where the center of gravity is located in the middle of the body length (a=0.85 m), we have $\alpha_1\cong6$ kg ms^2 and $\alpha_2\cong50$ kg m. Using the condition of Eq. (4) and assuming $T_1=0.1$ s and $T_2=1.0$ s, the characteristic equation may be rewritten as follows:

$$0.6\ s^3+6\ s^2+(K-5)\ s+(K-50)=0$$

$$K=K_1K_2$$

From the above the root locus is determined as illustrated in Figure 8. It is clear from this figure that the minimum condition is K>50 for stabilizing the posture control system, but that the response tends to be vibratory if the gain K is too big. On the other hand, the Bode's diagram for K=100 is shown in Figure 9, which



Characteristic Equation ;

$$0.6\,s^3 + 6\,s^2 + (K-5)\,s + (K-50) = 0$$

Fig. 8. Root locus.

carries also, for comparison, the frequency characteristics obtained from the experiments to determine the balancing function of human being discussed in the preceeding section. As a result, the assumption based on the linear approximation of H(s) is recognized to be valid as a whole. The same results evince the technological necessity of the conventional use of PD regulator for this portion. For constructing a mechanical model physically, it is necessary, as explained above, to have the gain constant as large as required. Accordingly, the transfer function of the compensating circuit was divided into the operation factor (T_2s+1) and the gain factor used relay elements, and the cascade connection of these was assumed, until a system of maintaining the balance of an inverted pendulum was finally constructed (Fig. 10). In order to confirm that the system could actually maintain its balance, a simulation was introduced by the use of an analogue computer. It was assumed that the inverted pendulum weighed 0.4 kg with a length of 0.5 m, the center of gravity corresponding to the fixed point of the pendulum. An example of the results of the above simulation is shown in Figures 11 and 12. From top to bottom are arranged the input angle, the output of the compensating circuit, the output of the relay circuit, the control moment by the muscles, and the output

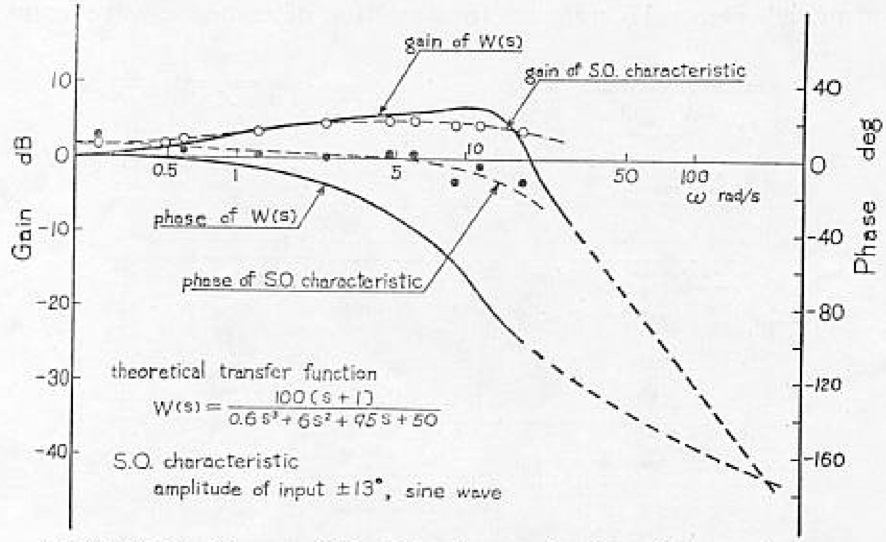


Fig. 9. Bode's diagram of the balancing mechanism of human being (comparison between theory and experiment).

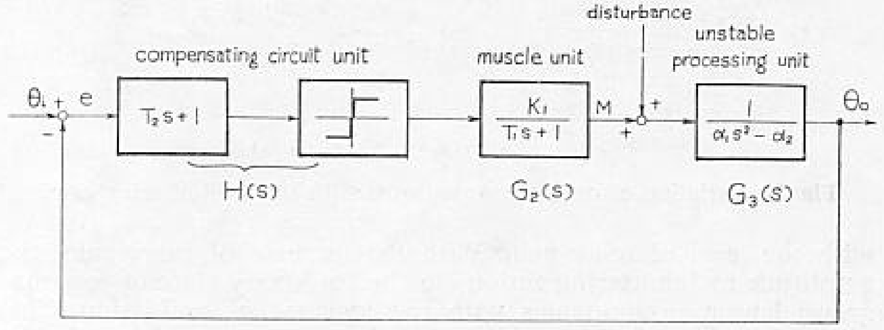
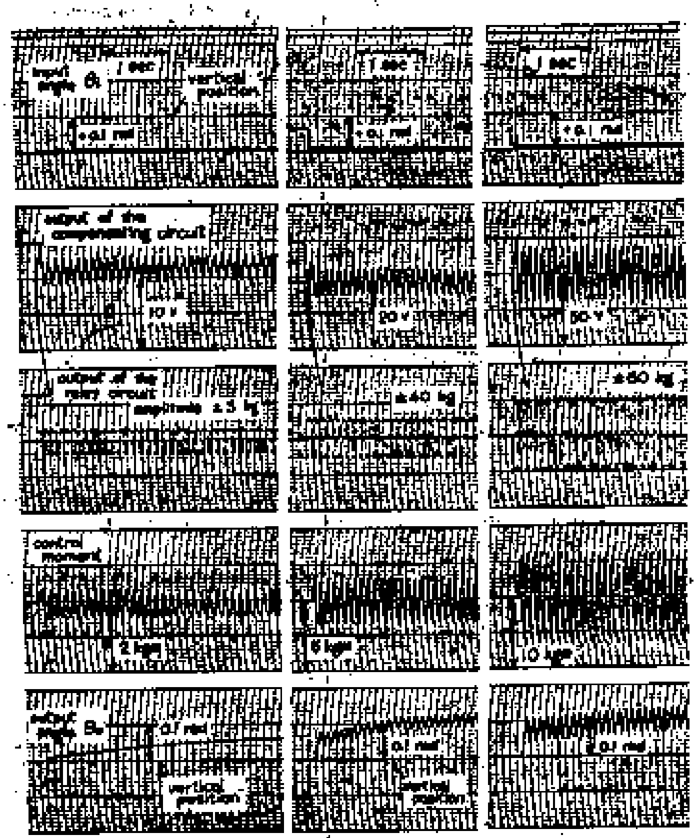


Fig. 10. Block diagram of posture control system.

angle. As is clear from the results, the inverted pendulum is prevented from falling and keeps its poise at a predetermined angular position. Thus it was established also by the computer model that the control system of such structure was applicable to the mechanical model. Figure 11 indicates the variation of response wave-forms with the level of relay gain. With the increase of relay gain, the amplitude of "chattering action" in the stationary state of response grows larger, accompanies with the increase of oscillation. This points out the unstable condition of the inverted pendulum in the neighbourhood of the equilibrium point. This effect was already discussed in connection with the root locus. Figure 12 illustrates the variation of response wave-from due to the difference in gain between the proportional element and the differential element in the compensating circuit. Letting deviation denoted by e, the



(a) ±3 (kg) (b) ±40 (kg) (c) ±60 (kg)

Fig. 11. Variation of response wave-forms with the level of relay gain.

composition is represented by $10\dot{e}+e$ in (a), $4\dot{e}+e$ in (b) and $\dot{e}+e$ in (c). In (a), the response is retarded and much settling time is required. In (b) and (c), rising is improved. This can be explained

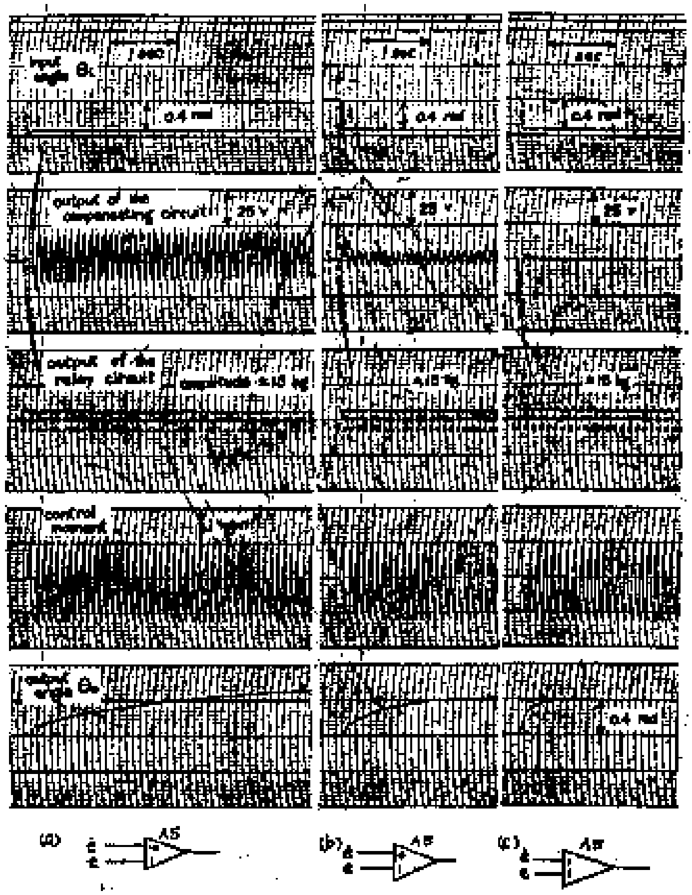


Fig. 12. Variation of response wave-form due to the difference in the compensating circuit.

also by the deviation phase plane trajectory in Figure 13. In a simplified system, there appears a trajectory having a saddle point on the division by one switching curve. With respect to the deviation phase plane $\dot{e}-e$, the above phenomena can be explained by the difference in response trajectory due to the inclination of the switching curve. In other words, with the increase of the time constant of the differential element, the switching curve changes from β_5 to β_4, β_3, β_2, and β_1 (Figure 13). In addition, β_5 indicates the case in which the switching curve coincides with the $\dot{e}$ axis, namely, the compensating element does not include the differential element. If the response trajectory is drawn according to the inclination on the phase plane, trajectories T_2, T_3, T_4 and T_5 are obtained each corresponding to β. Though the chattering effect accompanies all of these trajectories, the difference of the switching curve varies

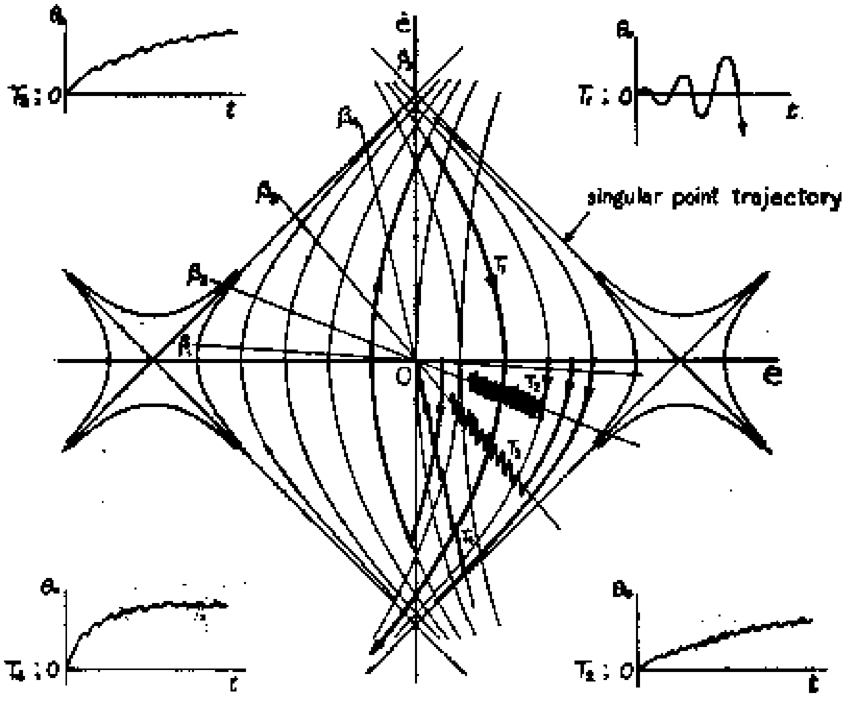


Fig. 13. Deviation phase plane trajectory.

the frequency of chattering and the time when chattering begins. Moreover, the settling time varies with the area surrounded by the response trajectory curve and the e axis. It follows that in case the area is smaller than T_4 (as with T_2), the settling time is increased. T_1 indicates the case in which the differential element is absent, where the response of the system enters into oscillation because of a slight overshoot.

A Trial Model of Posture Control System

The foregoing results were incorporated into an experimental mechanical model of the human balancing system. The model consists of two rigid levers (inverted pendulum), with the control moment provided by artificial rubber muscles. A composite block diagram of this system is given in Figure 14.

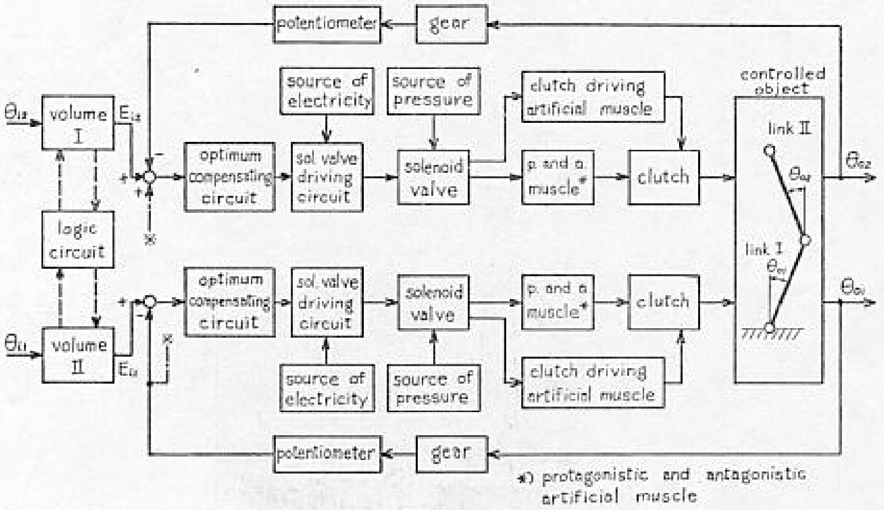
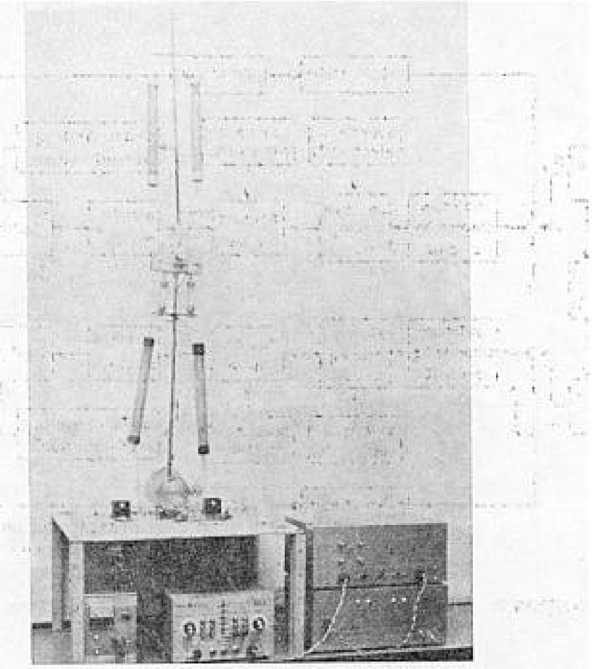


Fig. 14. Composite block diagram of the model of posture control system.

The controlled object maintains its balance in the following manner. First of all, the output angle θ_0 rad, is detected by a potentiometer and compared with the input, the deviation voltage going into the compensating circuit for information processing. To be specific, there is formed a voltage equivalent to the linear combination output of deviation e and ė. The output of compensating circuit drives a solenoid three-way valve in an on-off operation via the solenoid valve driving circuit. Thus the artificial rubber muscles function under pneumatic pressure, repeating the actions of protagonistic and antagonistic muscles so as to secure the posture of the controlled object in equilibrium. In this operation, a clutch mechanism make use of the artificial muscles works for switching between the protagonistic and antagonistic artificial muscles.

Photo 2 shows the entire view of the experimental model. There is an unstable link mechanism on the testing board, under which are provided the DC power source and input circuit device; on the right-hand side you can see the compensating operational circuit and the artificial rubber muscle driving circuit. Individual units are composed as follows:

a) Controlled Object: This is a two freedom unstable link mechanism in which two soft steel round bars are serially connected by means of a rotary joint. Figure 15 is a schematic drawing of the experimental model comprising the controlled object and the driving device. The upper axis II denotes the upper body and the lower axis I indicates the lower limbs.



ıoto. 2. Entire view of the experimental model.

b) Control System: The structure was devised in which artificial rubber-muscles were used in opposing pairs by way of the protagonistic and antagonistic muscles. The actuator could be installed in much the same positions as the human skeletal muscles, simply because of the light weight of the artificial muscle as discussed earlier. Alternation of the opposing muscular functions was achieved by a changeover clutch mechanism using also artificial rubber-muscles. In Figure 15, M_{A_1} is the protagonistic artificial rubber-muscle, and M_{A_2} is the clutch driving artificial rubber-muscle. So even if M_{A_1} is contracted, it will not function as the protagonist unless the clutch is turned on by M_{A_2}, so that the control torque will not occur on this side. The performance of M_{A_1} synchronizes with that of M_{A_2}, and besides the time constant of M_{A_2} is so small compared with that of M_{A_1} that very little contraction is required. For this reason, a small artificial muscle is used. The clutch device is made up of a pulley, stopper, gears, spring and artificial rubber-muscle. This is designed for an action analogous to the opposing function of skeletal muscles in the human body, and also for expanding the range of rotary motion of the link. The respective clutch devices for the axes I and II are structually the same.

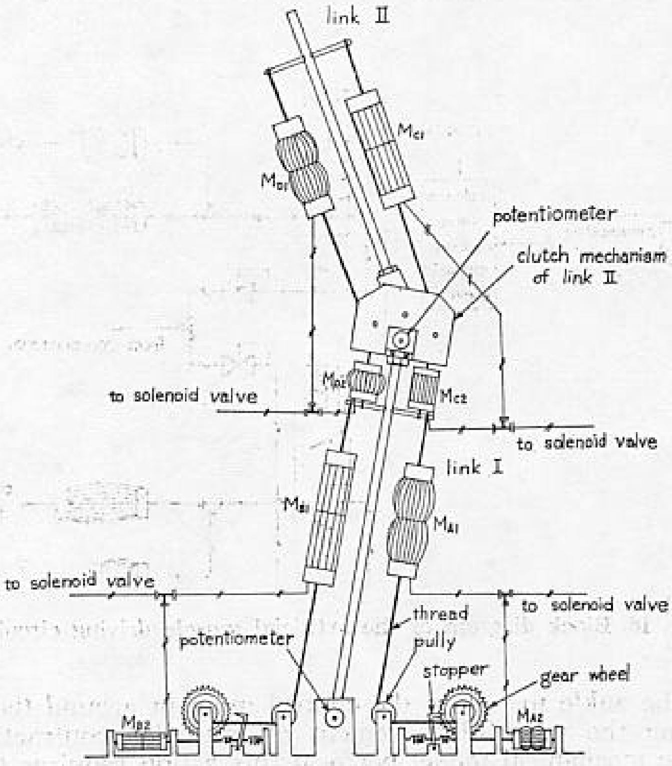


Fig. 15. Controlled object of the experimental model.

c) Detection Unit: The angular variation of each link is detected by the potentiometer provided on the respective axes of rotation of I and II.

d) Compensating Circuit Unit: With linear IC employed for the operational circuit, an analogue PD operational circuit is prepared compactly each for the control of the axes I and II.

e) Artificial Muscle Driving Circuit: A block diagram of the artificial muscle driving circuit is illustrated in Figure 16 in relation to the clutch mechanism.

f) Input Setting Unit: The setting of the command is performed by the angle setting volume in the input circuit. Comprising a logical circuit which may be called "bowing circuit", this device can transmit signals of order to the constructed balancing control system to make a bow. When a man bows, his upper body is inclined forward while the waist is pushed backward, forming as a whole the shape of "V" turned on its side and with a far more obtuse angle in the bending. This action is analyzed as an unconscious effort of the body to arrange that the central axis of gravity may fall on the ankle to reduce the control moment around the ankle, precluding the wasteful movement of muscular contraction. To make the mechanical model perform this action requires the geometrical definition of the relation between the input angles of the axes I and II. Figure 14 shows a logic circuit inserted on the basis of the calculation. Either θ_{l_2} in case θ_{l_1} is determined by higher manifestation or θ_{l_1} in case θ_{l_2} is determined is given by this circuit. This experimental apparatus, though being a simple system, has made it possible to assume any given posture and yet maneuver the center of gravity.

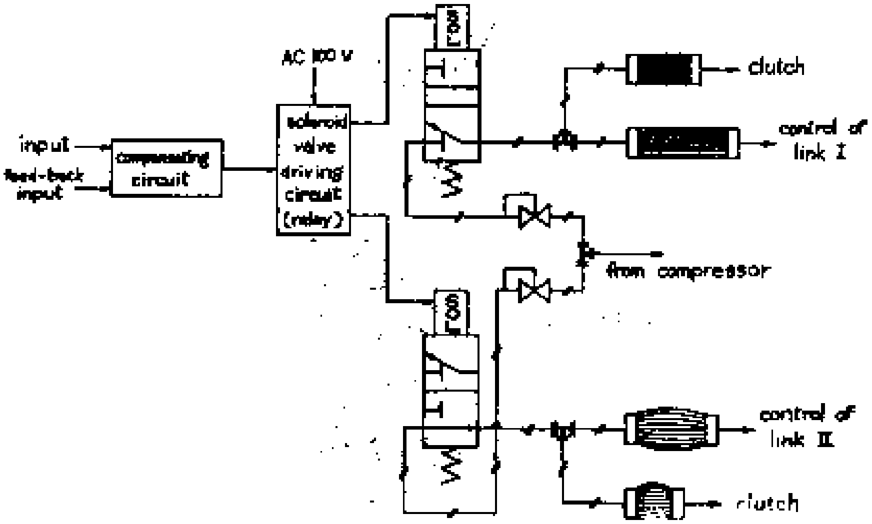


Fig. 16. Block diagram of the artificial muscle driving circuit.

The experiment made on the model was two-types: posture control by means of the axis I alone, and the simultaneous control with the axes I and II. In either case, the system was controlled to maintain balance at predetermined positions though vibrating due to the repeated chattering conformable to the theoretical expectation. Photo 3 shows how the system acted during its performance. It was proved that in the case of controlling both axes I and II, where the axis I was affected by the axis II, adequate balance control was accomplished while the axis I took care of the effect of the axis II as external disturbance.

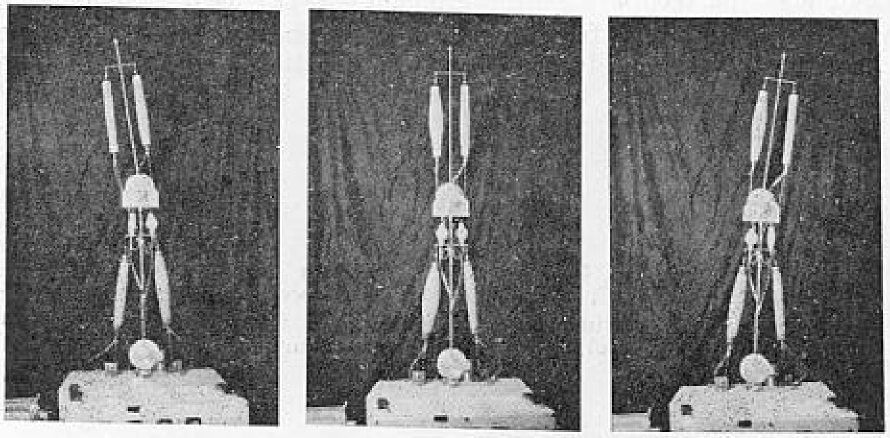


Photo. 3. Action of the experimental model.

Conclusion

In the trial manufacture of a model of posture control system, the control mechanism was studied from the viewpoint of control engineering on the basis of experimental results on the characteristic of the human balancing function. In the analysis of the mechanism, the human body was regarded as an inverted pendulum. Although the human body is essentially a multi-link mechanism with its members connected in series by rotary joints, the system was simplified for the purpose of a computer model so that a simulation of an inverted pendulum was considered, while the interaction with another inverted pendulum was handled as external disturbance to the control moment. This arangement was based on the technical concept of decomposing the system.

The tentative mechanical model was defective in that it could not perform easily actions involving exceedingly great angular change. Except for this point, an anticipated system could be constructed in which the unstable inverted pendulum could stand upright in a stable condition.

For an optimum control system in the criterion of minimum energy consumption during performance, it is indispensable to use a saturation element in place of the relay element in the trial mechanical model. In other words, it is desirable to have a dual mode system which acts as a linear system for small deflection angle and as an on-off system for large deflection angle. It was also established from the invariance theory that when the parameter of the system is changed (e.g., the human body is loaded with some weight), the prerequisite for the increased adaptability of the system is not only the angular change for the amount of feedback, but also the feedback of the moment (force) as a dual amount.

It is felt that future research must be concerned with the increase of stability in the walking of artificial legs, and furthermore, efforts should be made to develop a biped automaton.

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