Biomechanical Movement Analysis Regarding the Aspect of Energy Input

G. Hochmuth

Research Institute for Physical Culture and Sport, Leipzig, G.D.R.

Impulse for the developmental steps in Biomechanics have frequently been provided by the continuous progress in modern age sciences and technologies, too. During the last few decades a completely new and higher quality has been established in the field of kinemetry by the application of Video technology. The three-dimensional motion analysis from film pictures have been perfected in measuring procedures to a point making it almost a routine method nowadays. Laser technology brought progress for the distance-time measurements as for the transducers of values measured during dynamometric investigations in a decisive scale.

At the same time computer technology recently formed and accelerated this progress essentially. Applying computer technologies it was possible to enter into measuring technological problems when movements were to be analysed biomechanically, which could not be solved in the past because of their huge amounts of evaluational and calculational efforts, as e.g. the projective correction of the motion film analysis, the levelling of falsified measuring signal dynamics, or the simulation of movements of the human locomotor system.

Biomechanical modelling could only be started at high gear by applying computer technologies. At this time we find that biomechanical modelling has become an important main line of biomechanical research work everywhere, and tasks to be solved are approached on a wide scale.

Connected therewith, biomechanical theories and methodology have also made some progress. This concerns mainly the theoretical constructions to assess the suitability and efficiency of athletic movements, i.e. those criteria that have to be utilized when movements have to be assessed afterwards. One should have such criteria at his disposal particularly whenever computerized optimisations shall be carried out by means of modelling and simulating to justify generalized statements, as compared with the description of certain single cases.

Relating the actual boom of software developments in Biomechanics to the progress made in theoretical positions, the latter must be defined as being rather modest ones. These are the reasons why a stronger approach towards theory formation in Biomechanics seems to be urgently necessary.

We want to point out here a decisive aspect as far as biomechanical movement analyses are concerned that has — according to our point of view — been taken into consideration only insufficiently or not at all in the past, thereby resulting in incomplete or even wrong assessments of reality.

With the exception of athletic movements in endurance sports the energetic input per time unit (mechanical performance) has been considered to a small extent only in Biomechanics. In endurance sports attention was mainly focussed upon the bio-energetic aspect (metabolism and availability of energy), and less upon mechanical performance.

Taking the biologically developed muscular strength for granted in Biomechanics and considering it primarily the mechanical cause for human movements the relations between dynamics and kinematics, between force and motor impulses can be enlightened and represented by means of Newton's 2nd axiom only.

NEWTON (2nd axiom)

$$F_a = m \cdot a$$

Force = mass × acceleration

Dynamical Fundamental Lwa

$$\int_{t_1}^{t_2} F_a(t)dt = m(V_2 - V_1)$$

Force impulse = Changes of movement impulse

$$F_a = F_{muscle} - F_{resistance}$$

↓ (F_{muscle})

Independent value?

Mechanical cause of movement?

That point of view would presuppose tha t no other mechanical reason is necessary for the mechanical movement of the human, locomotor system. This means that the lines where Biology and Mechanics meet may be located in muscular force by entering the mechanical effects of muscular tensions produced by biological processes as mechanically independent values $F_{musc.}$ into the equations for the interplay of forces.

It seems, however, obvious that we must not start from such presuppositions. Sport practice gave evidences for that quite frequently. Theoretical positions of that kind have e.g. led to the wrong attitude that the maximum force contributions which can be developed from a muscular group during strength tests with motorically simple movements and under load conditions basically characterized the levels of strength capacity of that muscular group and should principally be achievable also in motorically more complicated and faster movements. (Putting it into the simple language during training sessions: «Strength is there but cannot be utilized»).

Starting from energetic reflections one is forced into another opinion. It holds that muscular strength must not be considered — also from the mechanical point of view — an independent value or primarily the mechanical cause for human movements. Just like any mechanical motor system, there must be energy applied, motor work performed to dislocate masses. That means: the energy input from the accelerative work performed by muscles represents the original cause for the mechanical movement of human locomotor systems. The kinetic energy of moved sub-masses will be increased by accelerative work or decreased by decelerative work.

EVERGETIC REFLECTIONS

$$\int_{S_1}^{S_2} P_a(s)ds = \frac{m}{2} (v_2^2 - v_1^2)$$

Accelerative work = Increase of kinetic energy

$$P_a(t) = \frac{d\, E_{kin}^n(t)}{dt} \quad \text{Accelerative performance}$$

The energetical input per time unit, the mechanical accelerative performance $P_a(t)$, is essential for the efficiency of the drive. Despite the fact that the energy input is the original cause for movements the energy supply in time (the mechanical performance P) depends on further mechanical factors, as on the suitability of motor structures, and on the working conditions. The highest effect (largest increase of kinetic energy) can be achieved if the time integral of the dynamics of accelerative performances becomes a maximum. That necessitates an adequate motor structure and optimal working conditions.

$$\triangle E_{kin} \rightarrow \text{maximum, if:}$$

$$\int_{t_1}^{t_2} P_a(t)dt = \int_{t_1}^{t_2} F_a(t) \cdot v(t)dt \rightarrow \text{maximum}$$

From that mathematical relation it becomes obvious that both values, the accelerative force F_a and the track velocity v of the moved mass (in the case of translation) are essential. The product from both characterizes the actual value of mechanical performance.

Now, we want to attempt to consolidate more closely this theoretical position tabled here as the conclusions for the approach to biomechanical movement analyses to be drawn therefrom, and to explain it (Fig. 1).

As early as in the twenties Hill could make an important statement regarding muscular performances when he experimented with isolated muscles from animals. He had measured the maximum contractile velocities for varying resistance forces F_{load} against which the artificially stimulated muscle contraced, and determined the function $v_{max}=f(F_{load})$. He found that the maximum total performance from an external mechanical performance $F_{load} \cdot V_{max}$ and an internal performance (characterized by the two constant values a and b) is always equally large, irrespective of the size of the resisting force.

That result includes already the statement that a maximum value of performance (i.e. a limit value of performance) that cannot be passed may be assumed for a given muscle unter corresponding working conditions.

One must obviously start from the fact when muscular drives of human locomotor systems are analysed that a certain performance limitation is given for the corresponding level of training fitness. Before we will turn towards that question we want to assess first the performance values that could be expected.

As can be seen in Figure 2 a body of 80 kg mass shall be accelerated

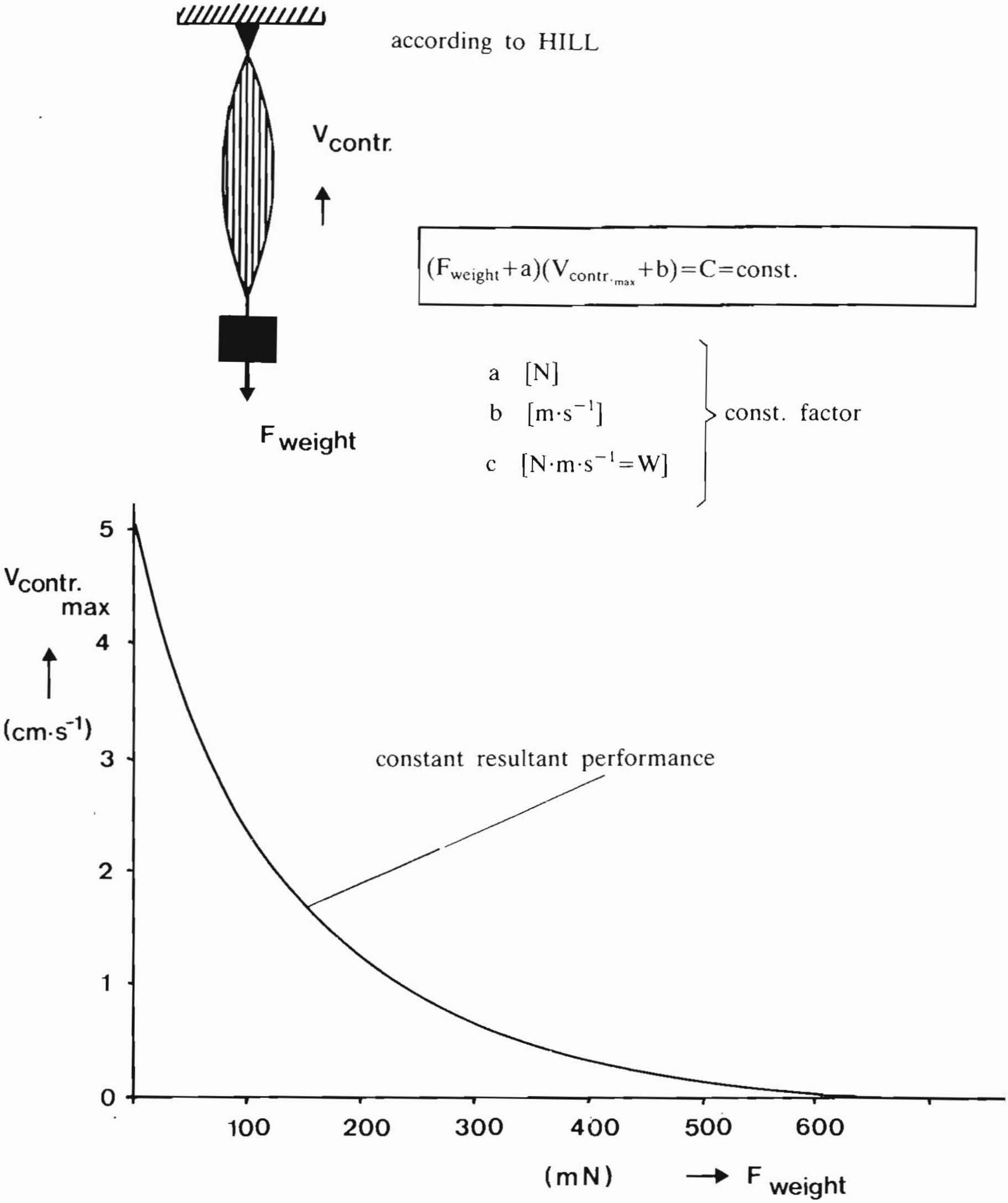
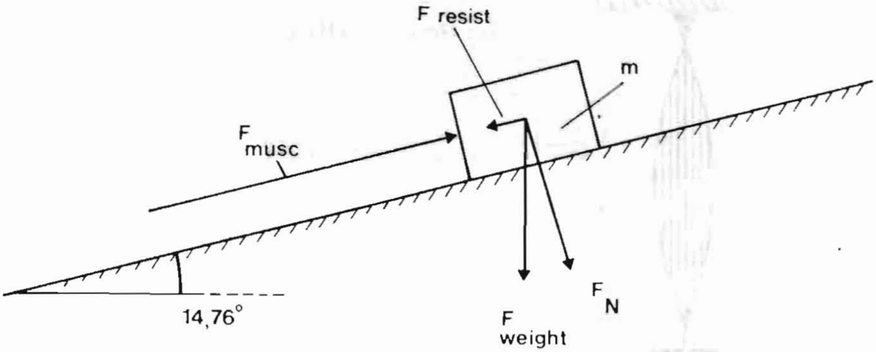

according to HILL
V contr.
(F weight + a)(V contr. max + b) = C = const.
a [N]
b [m·s⁻¹]
c [N·m·s⁻¹ = W]
const. factor
F weight
5
V contr. max
4
(cm·s⁻¹)
3
constant resultant performance
2
1
0
100
200
300
400
500
600
(mN)
→ F weight

Fig. 1



$F_{frict.} = \mu \cdot F_N \approx 0$

$m = 80\ Kg$
$F_{muscul.} = 1.800\ N$
$F_{resist.} = 200\ N$

$$F_a = F_{muscul.} - F_{resit.} = 1.800\ N - 200\ N = 1.600\ N$$

$$a = \frac{F_a}{m} = \frac{1.600}{80} = 20\ m \cdot s^{-2}$$

Fig. 2

upwards by muscular strength along an oblique track. For the reason of our reflection we assume that no friction resistance is existent. In addition to that we start from a constant acceleration requiring only simple calculations. For the example given there shall be a constantly acting muscular force of $F_{musc.} = 1.800$ N so that — at a track resistance force of F=200 W — a constant accelerative force of $F_a = 1.600$ N is effective, resulting in a constant acceleration of $a = 20\ ms^{-2}$.

In Figure 3 the time dynamics for the velocity v, the working distance s, the kinetic energy E_{kin} and the accelerative performance P_a are presented for that accelerative process in four diagrams.

Now, two stages with an equally large increase of velocity of 1 ms^{-1} should be compared (cf. Fig. 4):
Stage from 1 to 1 ms^{-1} (from 0 to 0.05 s), and
Stage from 3 to 4 ms^{-1} (from 0.15 to 0.20 s).

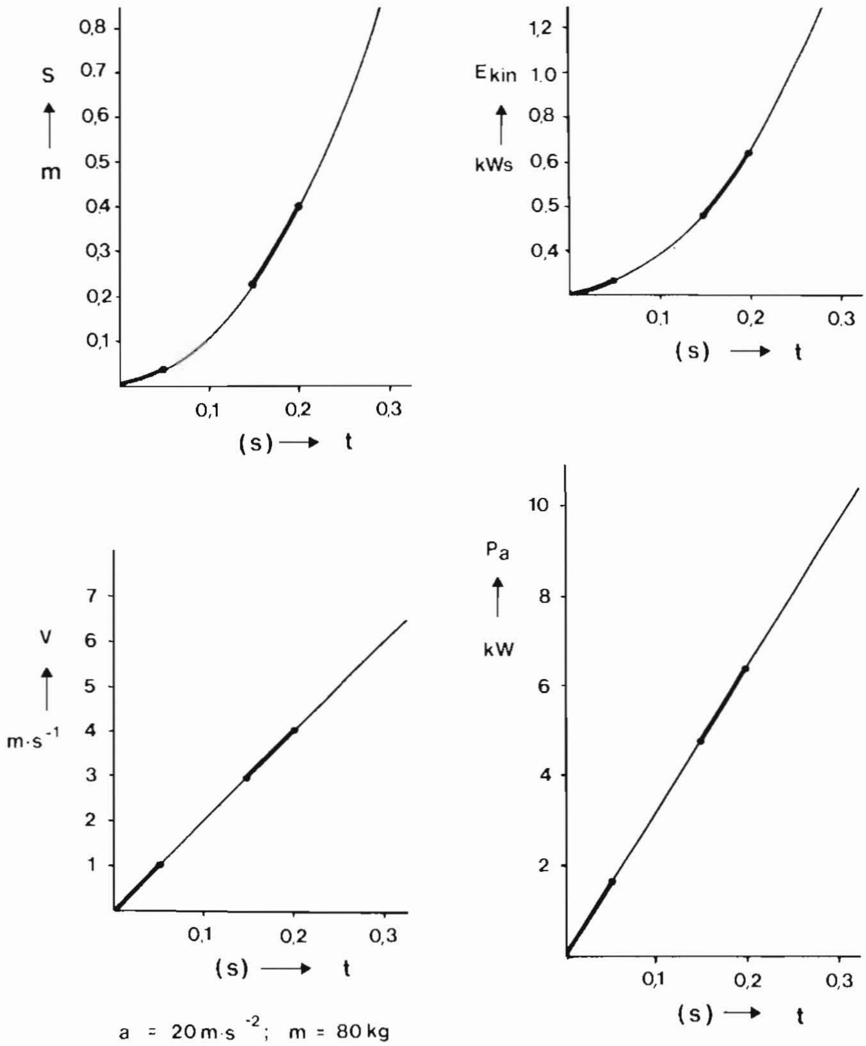

s
m
0,8
0.7
0,6
0.5
0.4
0,3
0,2
0,1
0,1
0,2
0,3
(s) t
Ekin
kWs
1,2
1.0
0,8
0,6
0.5
0,4
0,1
0,2
0.3
(s) t
v
m·s-1
7
6
5
4
3
2
1
0,1
0,2
0,3
(s) t
a = 20 m·s-2; m = 80 kg
Pa
kW
10
8
6
4
2
0,1
0,2
0,3
(s) t

Fig. 3

		velocity	v[m·s^{-1}]
		0 → 1,0	3,0 → 4,0
time [s]	t	0 → 0,05	0,15 → 0,20
working path [m]	s	0 → 0,025	0,225 → 0,400
	Δ_s	0,025	0,175
energy [W·s] or [N·m]	E_{kin}	0 → 40	360 → 640
	ΔE_{kin}	40	280
power [W]	P_a	0 → 1.600	4.800 → 6.400
	$\bar{P}_{a_{aver}}$	800	5.600

Fig. 4

Working Distance

In the lower ranges of velocity from O to 1 ms^{-1} only 0.025 m (i.e. 2.5 cm) as compared with 0.175 m (17.5 cm) are covered in the higher velocity range. That is the sevenfold distance.

Kinetic Energy

The kinetic energy is increasing from 40·s in lower velocity ranges up to 280 W·s in higher ones; i.e. also the sevenfold value.

Accelerative Performance

The sevenfold higher value has also been found in the accelerative performance in higher velocity ranges. The average accelerative performance is increased from 800 W to 5.600 W within the stages that have been analysed.

From the aspects of energetical input and temporal energy supply (the mechanical performance) there is thus an essential difference, whether the velocity of a mass is increased by an equally large amount at a lower or higher level of velocity, i.e. whether the equally large accelerative force must be produced at a low or at a high velocity.

Like all mechanical drives in nature and technology, we have to start also with muscular drives from the fact that an athlete's mechanical performances are limited by his (or her) actual level of training fitness, and the quality of his (or her) working systems lies eventually in his (or her) capacity to achieve high mechanical performances.

Through a longer period we have experimentally studied the situation which is present in relation to the mechanical performance reached during leg and arm extensions. We used the test construction shown in Fig. 5 to analyse leg extensions. The subjects tested were lying in a supine position and were asked to jerk a mass unit vertically upwards. Jerking could be prepared by lowering the unit so that an initial force had already been produced at the return point when the accelerative impulse was beginning.

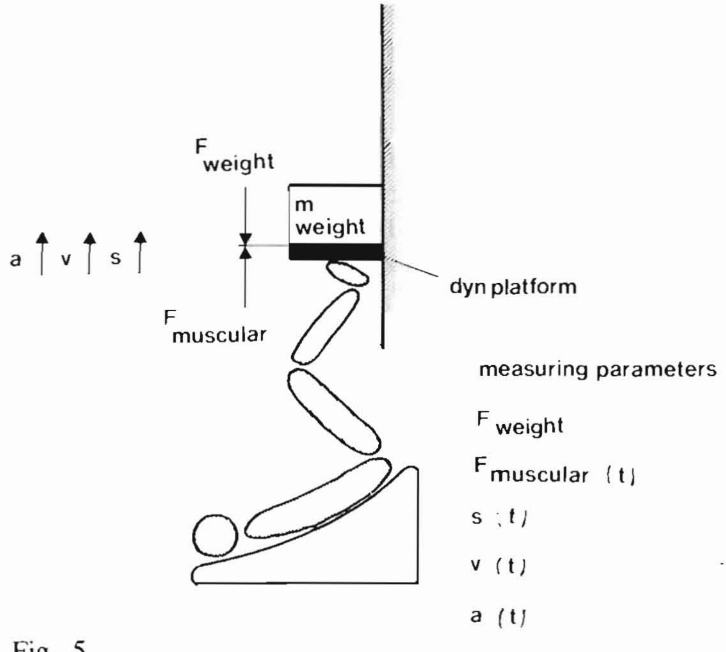


Fig. 5

The mass unit was guided by a sledge and caught after the jerk-off during the trajectory phase. Below the body a dynamometric platform was located to measure the temporal dynamics of the muscular force $F_M(t)$. The mass of the unit to be accelerated could be varied. In addition to that the temporal dynamics of the distance, velocity and acceleration of the body mass were separately assessed with corresponding measurement procedures. Measuring values were automatically registered, calculated by a computer into the path dynamics of the forces, velocities and mechanical performances, and graphically presented.

In Figure 6 the path dynamics of the force, velocity and the perfomance have been arranged parallel to each other for the lowest and highest load levels (left F_{load}=1,100 N, right F_{load}=500 N). As is already well-known, an essentially higher situated force curve was resulting from higher loads as compared to a correspondingly lower one for velocity. The performance dynamics are, however, almost equal. At lower loads the performance curve is even somewhat higher situated. Similar tendencies could be found regarding the accelerative work (hatched areas in the F-s dynamics).

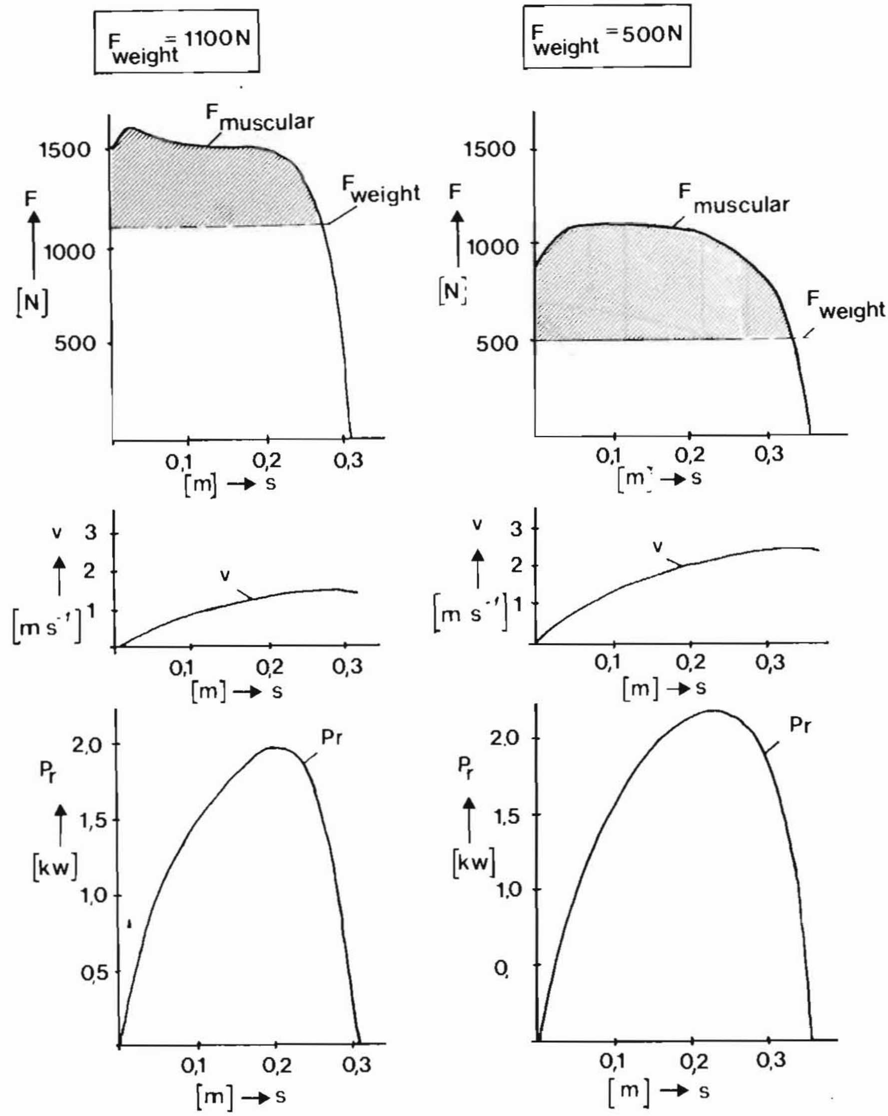
In Figure 7 the performance-distance dynamics are presented for all the load levels. Except the curve for maximum loads (F_{load}=1.100 N) there are almost identical dynamics.

Dotting the maximum values of mechanical performances against the load the load characteristic line will result as shown in the diagram of Figure 8 (upper curve). Several studies with subjects of varying athletic potentials resulted always in the same typical dynamics of the load characteristic curve for their maximum mechanical total performances. These curve dynamics are characterized by a plateau at a certain medium load level that is declining as well towards the smaller as to the higher load values. (The load range below 500 N which had not been studied during that example was drawn as a dash line).

Having used the terms «mechanical total performance» and «accelerative performance» several times, I now want to explain them. According to the various forces acting during accelerative or decelerative processes in athletic movements we distinguish equally a mechanical

— total
— accelerative (or decelerative), and
— transational or lifting performance.

The actual value of a total performance is resulting — in the case of a transational movement — from the product of the actual values of muscular force and path velocity. The actual value of accelerative force



F weight = 1100 N
F weight = 500 N
F muscular
F weight
1500
1000
500
F
[N]
0,1
0,2
0,3
[m] → s
v
3
2
1
[m s-1]
Pr
2,0
1,5
1,0
0,5
[kw]

Fig. 6

Resultant muscular performance

(two-legged putting)

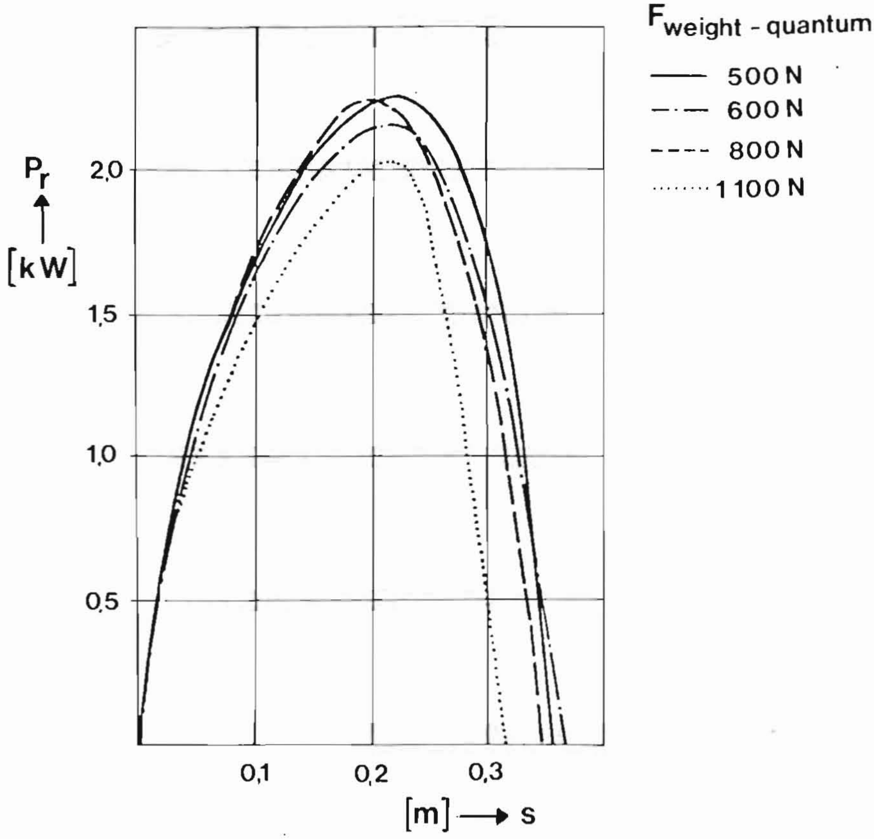


Fig. 7

Characteristics of $P_{r_{max}}$ – and $P_{a_{max}}$ – weight course

(two-legged putting)

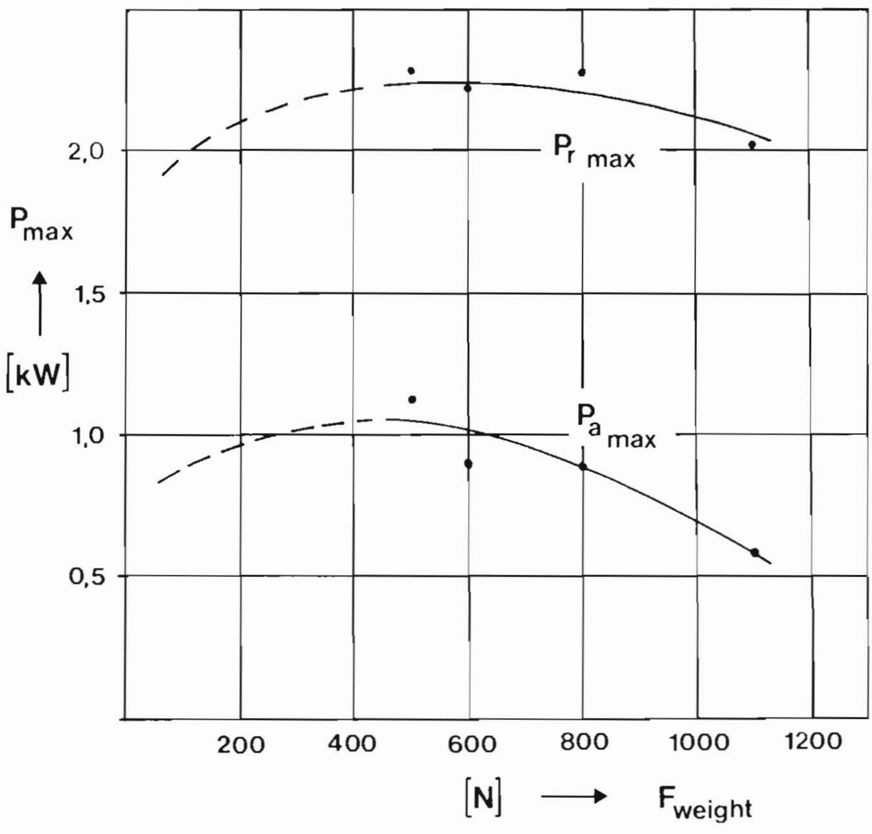
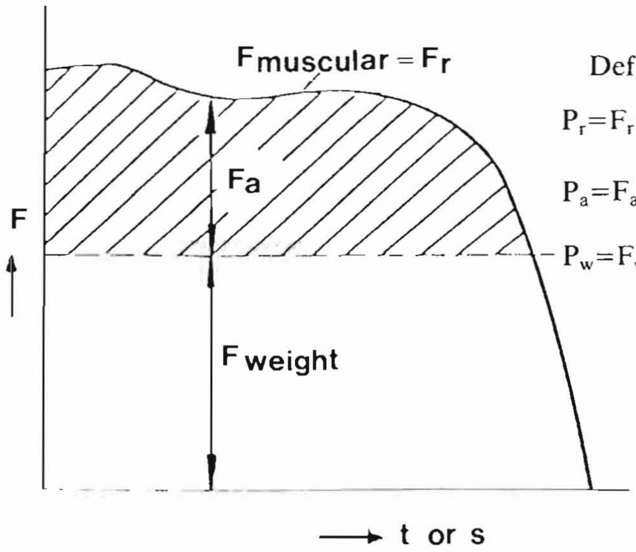


Fig. 8

should be applied for the actual value of an accelerative performance, that of resistance force for the actual translational or lifting performance.

The path dynamics of the accelerative performance P_a for the four load levels are shown in the lower diagram of Figure 9.



Definition

$P_r = F_r \cdot v$ resultant muscular performance
$P_a = F_a \cdot v$ accelaration performance
$P_w = F_w \cdot v$ weight or resistance performance

Acceleration performance (two-legged putting)

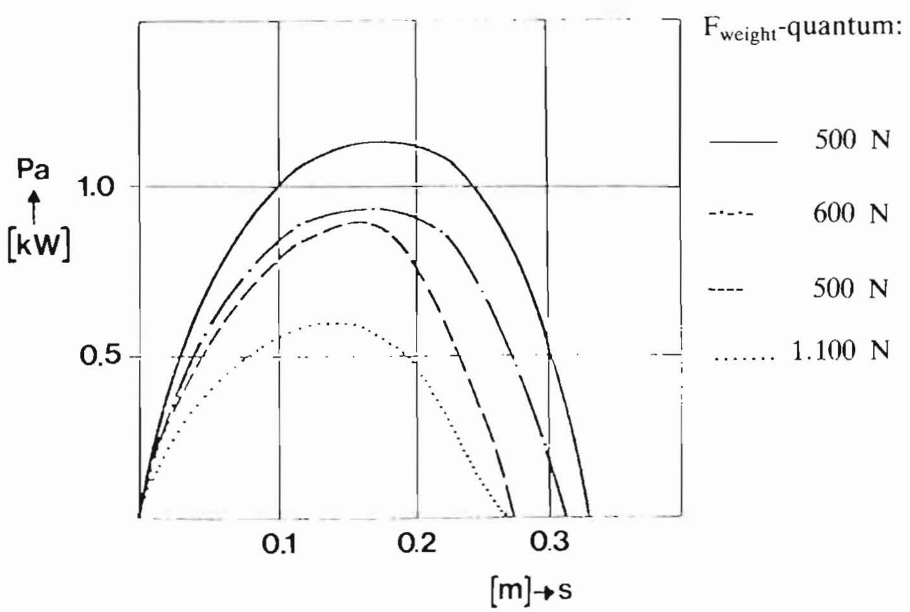


Fig. 9

From that diagram we can see that the load values are more and more decreasing when the loads are increasing. Presenting the load characteristic line for the maximum values of the accelerative performance (cf. lower curve in diagram of Fig. 8) one comes to the conclusion that it declines continuously with increasing loads. There is, however, a maximum within the curve dynamics which should be situated in that case as a load value of 500 N or somewhat lower.

In that example the optimal load for the maximum within the characteristic line of the accelerative performance could not exactly be determined since load levels below 500 N had not been completely tested. We know, however, from other load characteristics for leg extensions which we have registered several times, that such maximum is really esisting.

Jerking loads with the legs from a supine lying position — as shown here — a load of about 500 N corresponds approximately a Sargent jump in upright position without additional loads (acceleration of the individual's body weight).

Figure 10 shows the load characteristics of the maximum values for the mechanical total performance and accelerative performance in the two-arm jerk. The curve dynamics correspond rather equally to those when loads are jerked with both legs. It becomes obvious here that at the optimal load level for the maximum in the curve dynamics of the accelerative performance the plateau have not been completely reached within the dynamics of the total performance.

Generalizing we may state the characteristic curves of load dynamics for the bilateral jerk of loads, as well with legs as with arms, for the maximum values of the two mechanical performances: $P_{total^{max}}$ and $P_{a^{max}}$ as for the average muscular force $F_{musc.}$ The load curve for $P_{a^{max}}$ reaches its maximum at an optimal resistance force F_R. In the case of leg extensions the optimal load is identical with the individual's weight.

Near to the optimal load the plateau of the load characteristic line begins for $P_{total^{max}}$. (Fig. 11).

The average muscular force is continuously increasing with the growth of the load. These increases of force values in strength training exercises against resistances that are situated beyond the resistance forces of the competitive movements are frequently held as being the proper aims and objectives of strength training programs.

Finally we have studied the effects that come into play by various types of stength training in relation to mechanical performances. Experimenting with P.E. majors we compared two types for leg muscles:

Characteristics of $P_{r_{max}}$ – and $P_{a_{max}}$ – weight course

(two-armed putting)

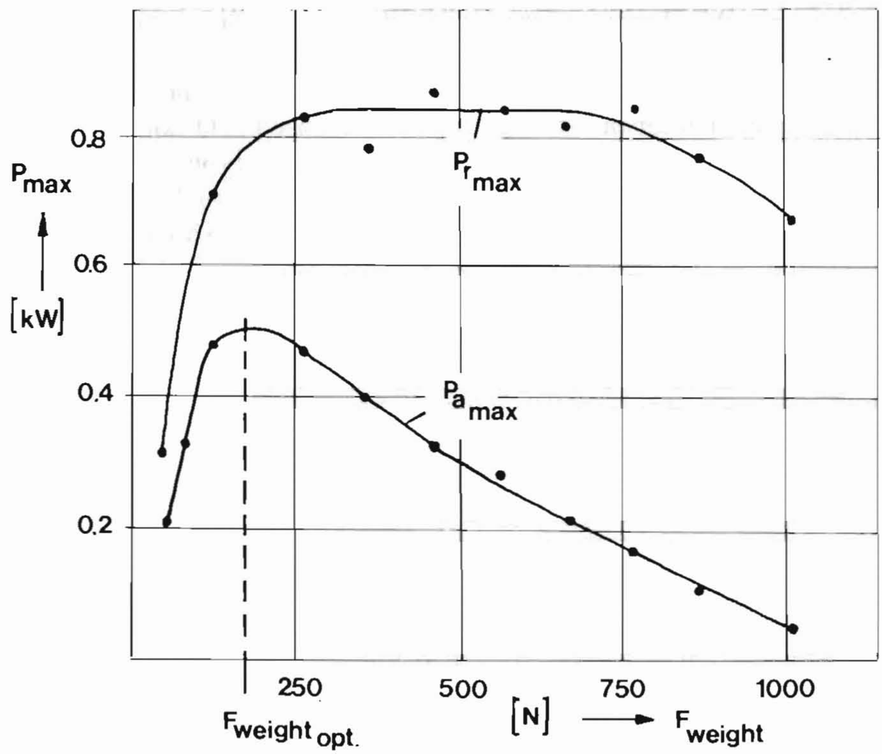


Fig. 10

A Against maximum loads

B At highest possible motor velocities with low to medium loads

The full lines in Figure 12 show the starting position for the distance or chronological dynamics of mechanical performance. By strength training A (maximum loads) an effect has been achieved that is shown in the dash lines. The performance curve is not raised by that type of strength training. The maximum value of performance was also not increased, however, the maximum of performance was reached earlier during the curve dynamics. That transition forwards results in a greater force impulse, i.e. in a larger accelerative work.

Typical courses of $P_{r_{max}}$ – $P_{a_{max}}$ – and $\overline{F}_{muscular}$ – weight curves

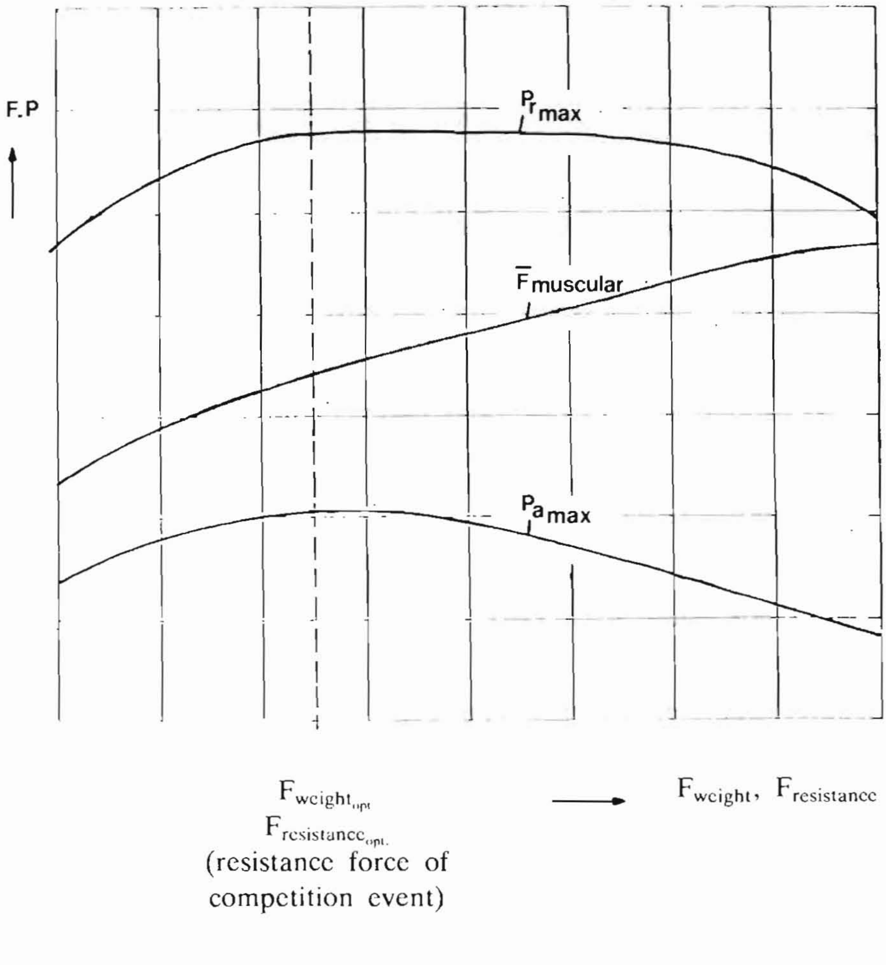


Fig. 11

The effect reached by strength training B was expressed by the dotted lines. The performance curve was raised, thus the maximum, too. Force impulses and accelerative work were as well increased.

For more exact analyses in Biomechanics it is often necessary to reach

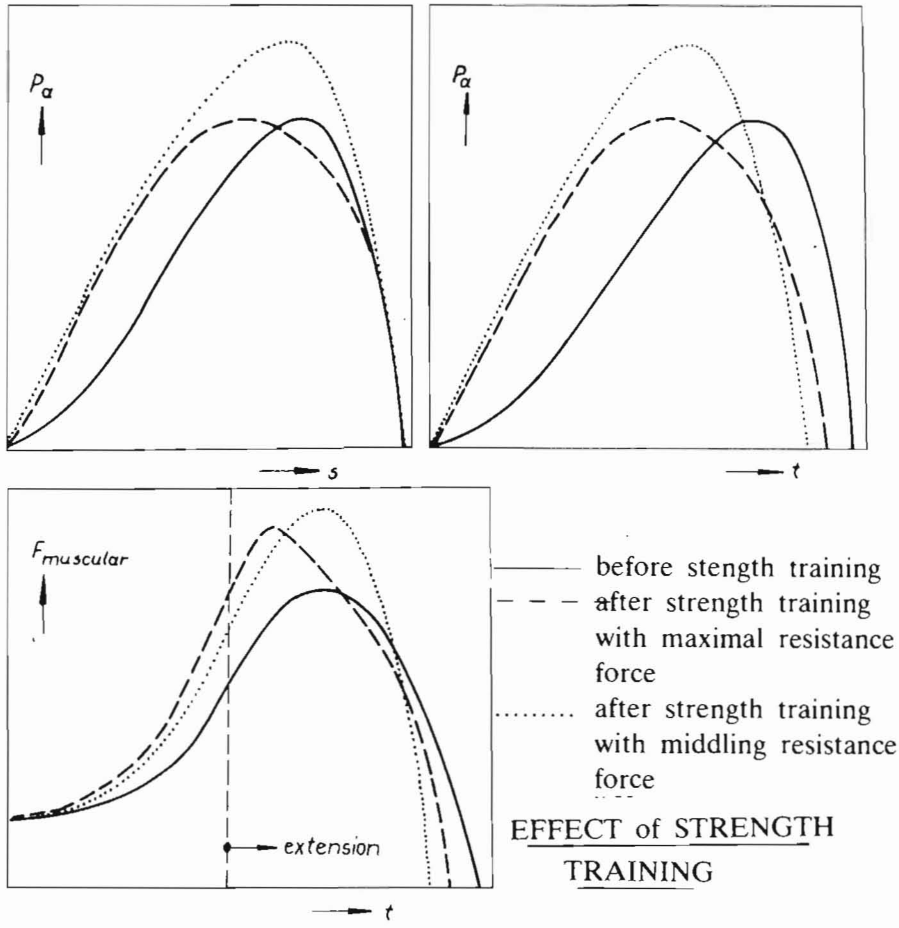


Fig. 12

the individual drives coupled with each other. We apply the segment chain model by knauf (cf. Fig. 13) for analyses of that kind. That model assumes that any joint possesses a muscular drive that is coupled with the neighbouring joints.

Rotational moments $Q = A\cdot\ddot{\psi}+B\cdot\Theta$

Angular acceleration $\ddot{\psi}=A^{-1}(Q-B\cdot\Theta)$

$$Q = \begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{pmatrix} \quad \ddot{\psi} = \begin{pmatrix} \ddot{\psi}_1 \\ \ddot{\psi}_2 \\ \vdots \\ \ddot{\psi}_n \end{pmatrix} \quad \Theta = \begin{pmatrix} \dot{\psi}_1^{\,2} \\ \dot{\psi}_2^{\,2} \\ \vdots \\ \dot{\psi}_n^{\,2} \end{pmatrix}$$

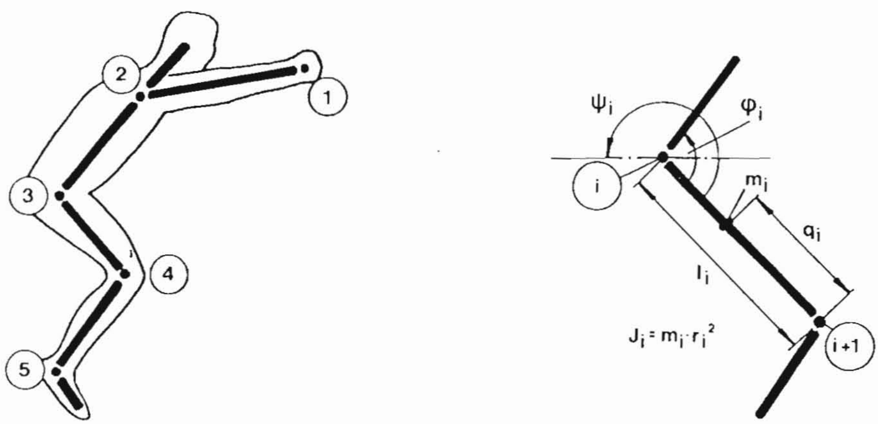
$$A_{ik} = D_{ik}\cos(\psi_i - \psi_k) \qquad i = 1 \cdots n$$
$$B_{ik} = D_{ik}\sin(\psi_i - \psi_k) \qquad k = 1 \cdots n$$
$$D_{ik} = D_{ik}(\lambda_j, \varepsilon_j, \mu_j, S_i^2)_i \qquad j = 1 \cdots N$$

$$\psi_i = \sum_{k=1}^{n} \varphi_k$$

In accordance with the task given one can start from the dynamics of force moments or from the angular acceleration, i.e. either from dynamics or from kinematics. Applying such segment chain model it becomes possible to assess also the perfomance dynamics of individual muscular drives. The segment chain model which is here shown is valid for the case of a free moved system, i.e. for the movements of individual body segments towards each other during the trajectory phase.

SEGMENT-MODEL according to KNAUF

(free system)



m_o – mass of body
l_o – height of body

$$\lambda_i = \frac{l_i}{l_o}$$

$$\varepsilon_i = \frac{q_i}{l_o}$$

$$q_i = \frac{r_i}{l_o}$$

$$\mu_i = \frac{m_i}{m_o}$$

Fig. 13

In the diagram of Figure 14 the dynamics of force moments M_3 and mechanical performarce F_3 are shown for the joint No. 3 (the hip-joint).

Moment of force of hip joint (M_3)
Performance of hip joint (P_3)

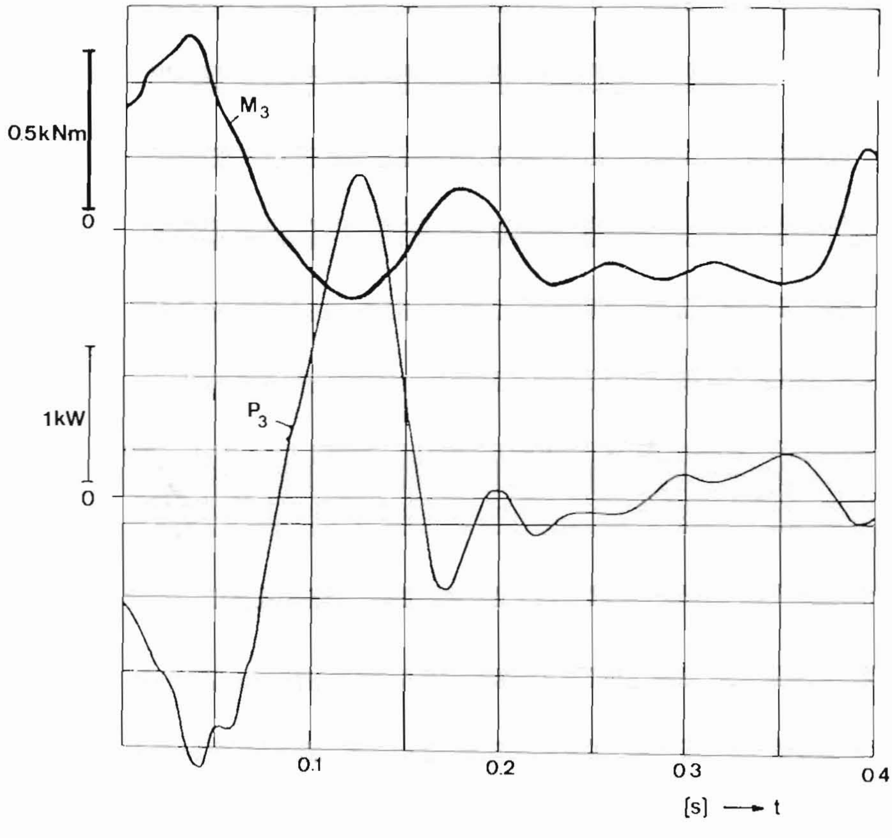


Fig. 14