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Segmental Contribution to Forces in Vertical Jump

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Summary. Performance of a vertical jump was analyzed with respect to the contribution of the different body segments to the forces acting on the whole body center of gravity. Both cinematograph and force-platform techniques were employed. The data disclosed that the take-off velocity in vertical jumps was caused by the different components as follows: knee extension 56%, plantar flexion 22%, trunk extension 10%, arm swing 10%, and head swing 2%. However, the average take-off velocity of the total performance (3.03 m/s) was only 76% from the theoretical maximum calculated from the segmental analyses. Optimal timing of the segmental performances was calculated to increase this "efficiency" to 84%. Great variance were observed among individuals in the total performance despite the similarities in utilization of the performance of individual segments.

Key words: Jumping mechanics – Efficiency – Coordination – Force-platform.

Determination of the efficiency of muscular activity has been an important subject of investigation in the area of biology of physical activity. Despite a bulk of information gathered on the subject, recent studies of Asmussen et al. (1974) in Copenhagen imply that the entire concept of mechanical efficiency should be reinvestigated thoroughly. For example, it has been shown that by a proper usage of muscle's elastic components one may be able to increase substantially the efficiency of running to the levels which may be twice as much as that during bicycling.

Normal human movements are usually very complex involving usage of several body segments. It is expected that part of the available energy is waisted during the simultaneous activation of several muscle groups. The present study was designed as a preliminary attempt to investigate the "efficiency" of a simple total performance as compared to performances of the different body segments. In short, the purpose of the study was to investigate the contribution of the different body segments to the performance in a vertical jump.

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Methods

Eight male athletes (six volley- and two basketball players) were used as subjects. Table 1 describes their structural characteristics including the lengths of each body segment used in the calculation of the present study. Each subject performed seven different movements on the force-platform. These trials were all performed separately from constant starting positions and they included the following movements of maximum intensity (Fig. 1 A–G):

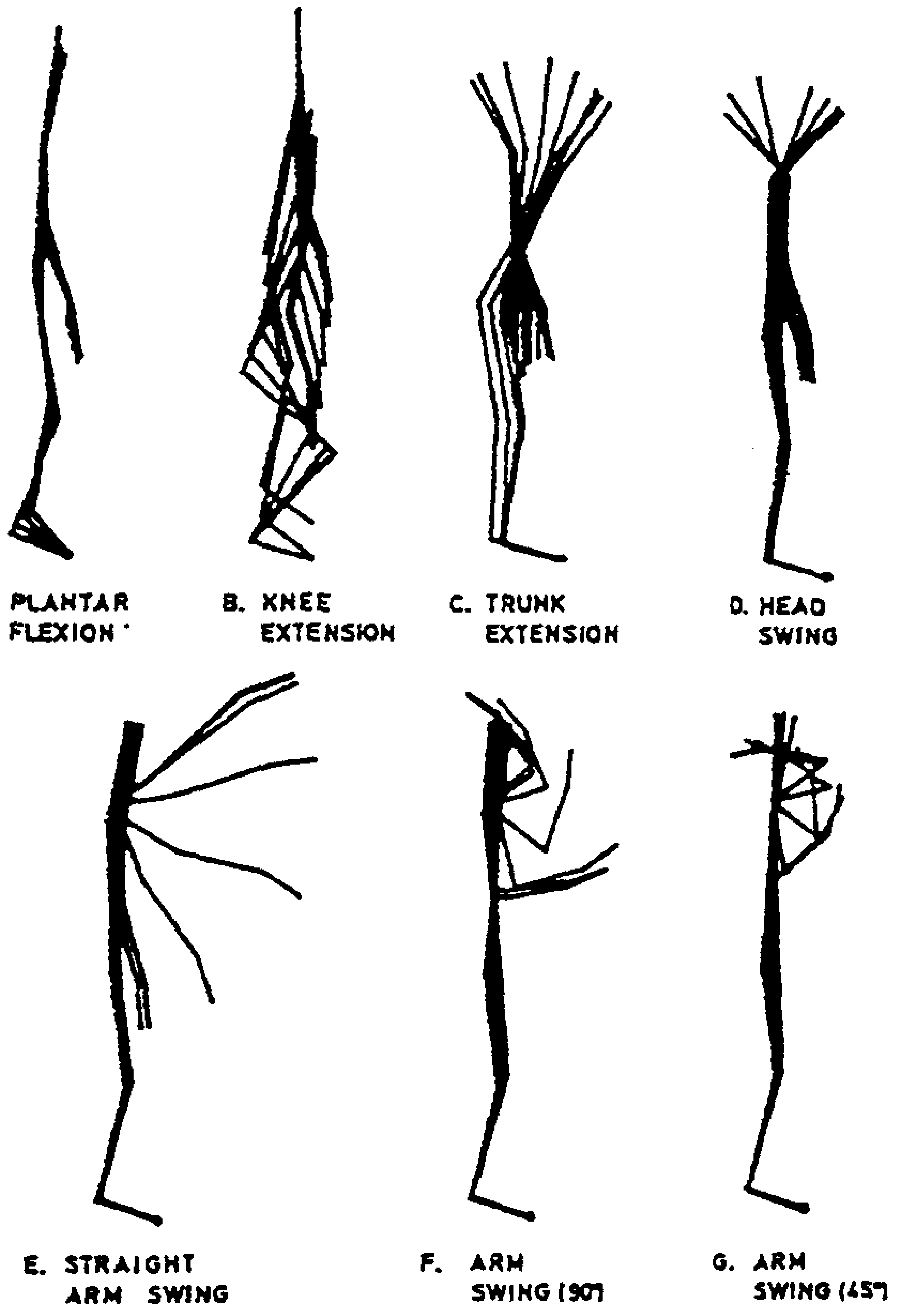

Fig. 1. Schematic description of each segmental performance A, B, C, D, E, F, and G

A. Planter flexion with the straight knees and ankle angle of 20°;
B. Knee extension from a 90° starting position and with the fixed (0°) ankle angle;
C. Trunk extension starting from a 40° flexion;
D. Head swing backwards from a full neck flexion;
E. Straight arm upward swing;
F. Upward arm swing with the 90° elbow angle;
G. Upward arm swing with the 45° elbow angle.

The subjects performed these movements several times, and the acceptance of the movement for analysis was based on two criteria: 1. Two observes had to agree that the movement was performed according to the instructions given; 2. The subject had to express whether he "felt" that his performance was successful.

In addition to these separate segmental movements, two maximal complete vertical jumps were performed from a fixed starting position as depicted in Figure 2. These jumps did not differ significantly from each other; therefore, their mean value was taken as an indication of the complete vertical jump (H). When performing the segmental movements or the complete jumps, the direction was always vertical and in B and H, where the subjects left the ground, the points of release and landing on the platform were always the same.

Table 1. Anthropometric characteristics of subject

Subject	Mass (kg)	Length (m)	Body segment lengths (m)					
			forearm	upper arm	trunk and head	thigh	shank	foot
1	73.5	1.87	0.31	0.30	0.88	0.48	0.48	0.29
2	61.5	1.81	0.31	0.32	0.85	0.44	0.49	0.31
3	83.0	1.92	0.37	0.34	0.91	0.47	0.52	0.32
4	58.0	1.76	0.32	0.33	0.79	0.46	0.47	0.29
5	69.0	1.88	0.33	0.33	0.91	0.47	0.49	0.33
6	80.0	1.95	0.34	0.33	0.89	0.52	0.53	0.31
7	72.0	1.68	0.27	0.29	0.81	0.39	0.41	0.28
8	85.0	1.84	0.33	0.32	0.87	0.46	0.45	0.29
Mean	72.8	1.83	0.32	0.32	0.86	0.46	0.48	0.30
S.E.	3.5	0.03	0.01	0.01	0.02	0.01	0.01	0.01

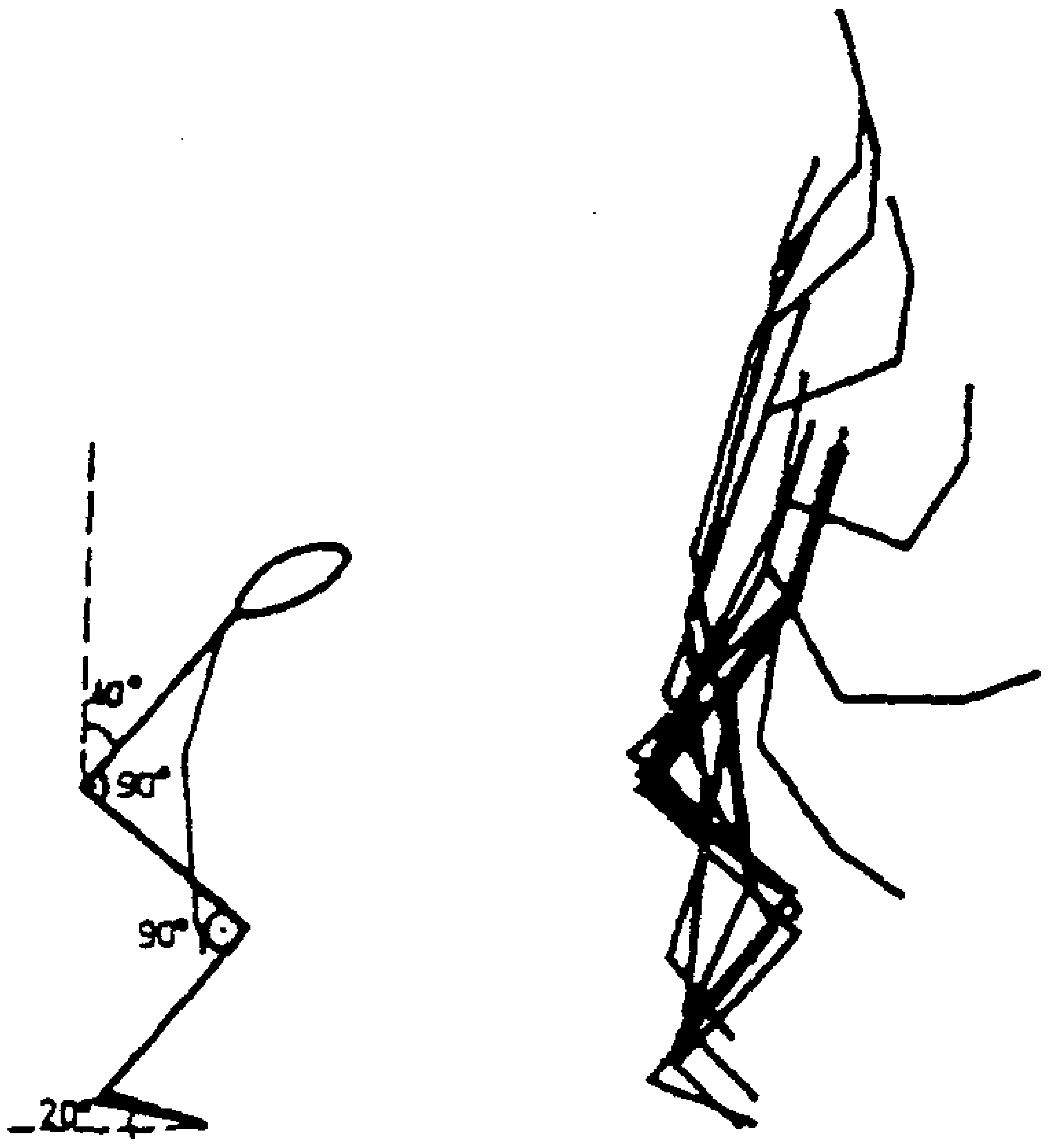

Fig. 2. The fixed take-off position (left) and the subsequent total vertical take-off performance (right)

In comparing the contribution of the different segmental and total performances (A–H) to the vertical jump, both the force-platform and film analysis techniques were employed. The vertical force record from the force-platform (Komi et al., 1974) was stored on magnetic tape (Philips Analog 7 Tape Recorder) and subsequently analyzed with a HP 9810 A Desk computer. The analysis of the release velocities for the center of gravities was done according to the analogy of force impulse and linear impulse as follows:

$$\int_{t_0}^{t_1} (F_y - G)dt = m(v_{y1} - v_{y0}),$$

where F_y = vertical force,
G = weight of subject,
m = mass of subject,
v_{y1} = vertical release velocity,
v_{y0} = 0.

Film analysis complemented the force-platform computation. Each performance was filmed with a Locam 51-0003 camera using a film speed of 100 frames per second. Dempster's (1955) segment parameters were used as references for computation of, e.g., segmental velocities, accelerations, forces and linear impulses.

The theoretical maximum vertical velocity (100%) was calculated from the positive net impulses in segmental performances (A, B, C, D, and as mean of E, F, and G). Similarly, positive net impulses were used to calculate the relative performance (%) of the total jumps (H) from the theoretical maximum.

The theoretical maximum velocity of center of gravity in jumps H was calculated from the segmental maximal velocities in these jumps according to the basic law of conservation of linear impulse.

For comparison of the different movements, time synchronization was performed on the basis of the release moment from the platform. In the movements, where no such release occured, the synchronization was based on the highest positon of trunk (always in C, D, and sometimes in A) and on the horizontal position of the upper arm (in E, F, and G). The error of synchronization was ± 0.01 s.

Results

The main results of the analysis are shown in Table 2. In total performances of the two trials, the mean net maximal reaction forces from the force-platform were 1005 ± 93 N (H). The respective release velocities (take-off velocities) were 3.03 ± 0.11 m/s (force-platform) and 3.08 ± 0.12 m/s (film analysis).

When the maximal values of linear momentum were calculated from the maximal segmental velocities of the total performance H, the average theoretical release velocity was 3.28 ± 0.11 m/s. On the basis of this, the different segments contributed to the total linear momentum as follows: hands 5%, forearms 8%, upper arms 9%, head and trunk 44%, thighs 16%, shanks 6% and feet 1%. These values are, in principle, similar to those reported by Miller (1976).

In segmental analysis (performances A–G) the theoretical maximum take off velocity was caused by the different components as follows (Fig. 3): knee extension

Table 2. Mean results of the selected parameters associated with the movement of the whole body center of gravity

Performance	Maximal vertical net force (N) Mean ± S.E.	Performance time (s) Mean ± S.E.	Vertical net impulse (Ns) Mean ± S.E.	Vertical theoretical take-off velocity (m/s) Mean ± S.E.
A	586 ± 40	0.163 ± 0.012	60.7 ± 3.2	0.86 ± 0.08
B	948 ± 66	0.274 ± 0.013	158.6 ± 6.9	2.22 ± 0.16
C	328 ± 53	0.193 ± 0.011	29.8 ± 3.3	0.42 ± 0.06
D	90 ± 10	0.121 ± 0.010	6.6 ± 0.1	0.10 ± 0.01
E	296 ± 19	0.247 ± 0.019	32.3 ± 2.2	0.45 ± 0.02
F	285 ± 22	0.200 ± 0.023	28.1 ± 2.0	0.39 ± 0.02
G	249 ± 11	0.192 ± 0.016	22.4 ± 0.3	0.31 ± 0.02
H	1005 ± 93	0.317 ± 0.011	220.2 ± 11.9	3.03 ± 0.11

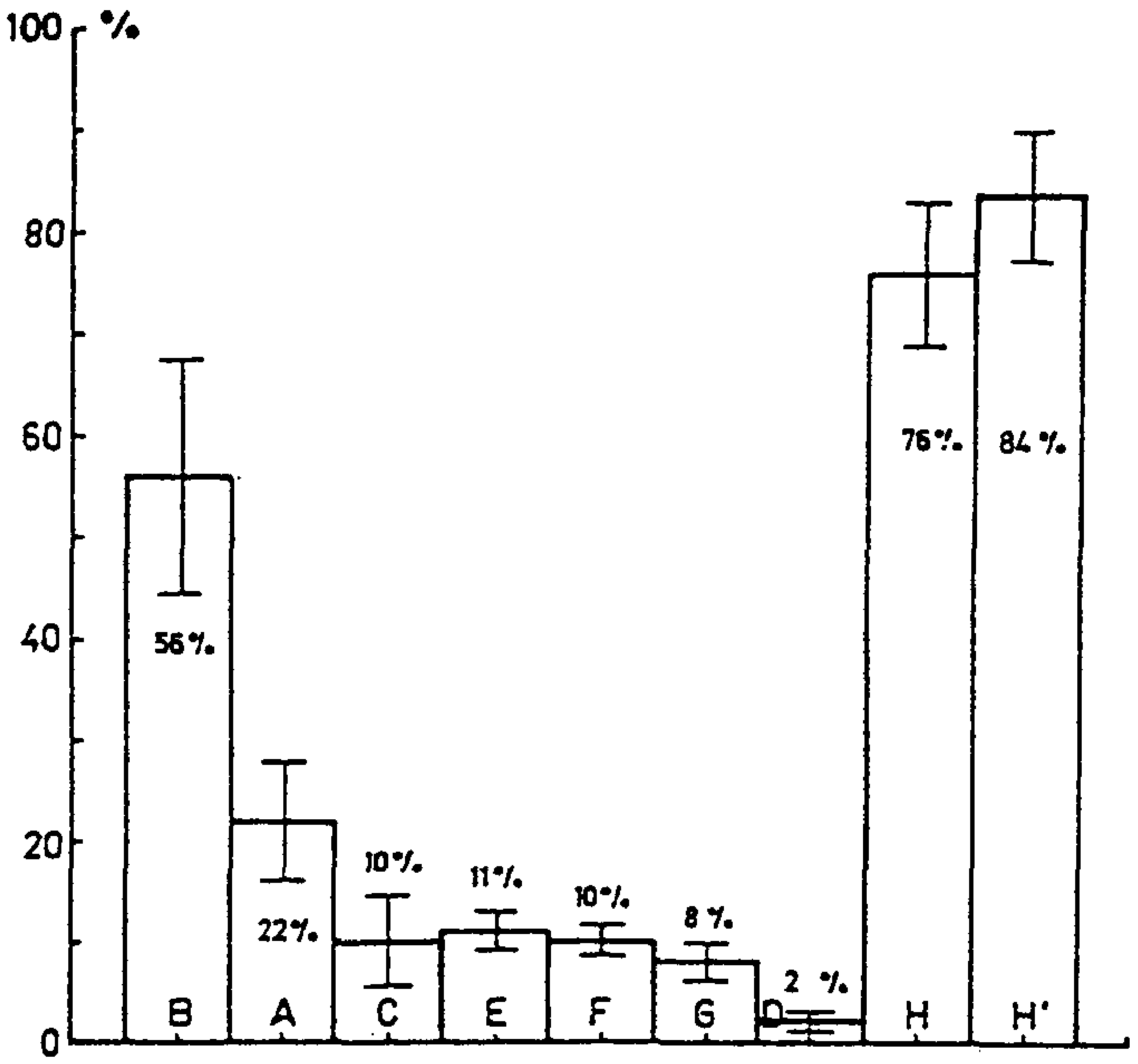

Fig. 3. The percent contribution of the maximal release velocities of the segmental performances (A, B, C, D, E, F, and G) and total performance (H, average of two trials) to the theoretical maximum take off velocity (100%) calculated from the positive segmental net impulses. H' denotes the theoretical maximal velocity of performance H

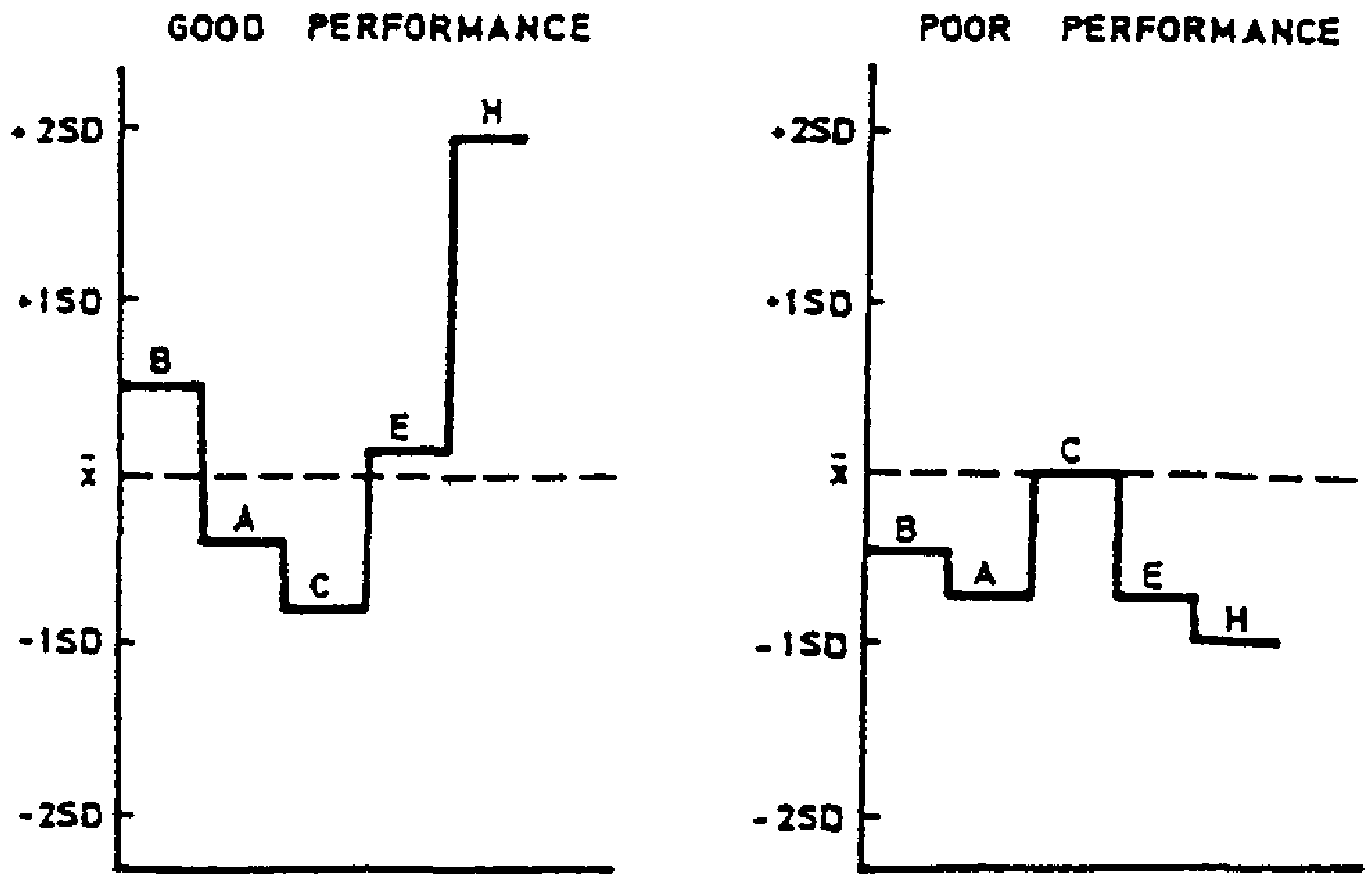

Fig. 4. Profiled description of good (subject 1) and poor (subject 7) performances. The figure shows the deviation of the performance of the selected segments (B knee extension, A plantar flexion, C trunk extension, E arm swing) and the total movements (H) from the group average ($\bar{x}$)

56%, plantar flexion 22%, trunk extension 10%, arm swing 10%, and head swing 2%.

The total performances, H, gave the take off-velocities which were, on the average, 76% from the theoretical maximum velocity calculated from the segmental net impulses. If in total performances the maximum release velocity is calculated from the segmental maxima. then these values are increased to 84%.

The various performances were standardized in segmental and total analysis. This standardization allowed the comparison of each subject with respect to the group averages. Figure 4 is an example of such a standardization showing two different performance profiles, where despite only slight differences between the segmental performances the total take off movements were characterized with much greater differences.

Discussion

In the experimental design of the present study it was assumed that the human body is composed of mechanically independent segments. On the other hand these segments were again assumed to be moved by forces which act on the whole body center of gravity. The most important result of the measurements was that the take-off velocity of the whole body center of gravity in the total performance was, on the average, only 76% as compared to the theoretical maximum velocity calculated from the segmental net impulses. This was despite the good athletic performance of the subjects.

The observed result thus suggest that a well trained person is able to utilize only $\frac{3}{4}$ of the available mechanical energy in the basic multijoint movement such as jumping. An important question then arises: What is the possible cause for the decreased efficiency in the total performances? One is reluctant to look for the mechanismic explanation from the problems of timing and coordination of the muscles affecting the movements of the different segments.

Looking at the problem purely from the standpoint of mechanics, one should expect that if the acceleration maxima of the different segments are exactly in phase then the performance is at maximum. In fact, Hochmuth (1975) has indicated with mathematical modelling that the time difference between the acceleration maxima of the different segments determines the final take off velocity. The smaller the difference the better the performance. This time difference in the present study was 0.15 ± 0.01 s for the total performance of H. The correlation coefficient ($r = -0.68$; $p < 0.01$) calculated between the time differences in the velocity maxima for the lower segments of the body (trunk, thigh, shank, foot) and the take-off velocity agrees well with Hochmuth's mathematical curve.

Timing in a multijoint motion can be referred to as coordination of the muscles affecting the movements of the various segments. On the other hand the level of coordination depends on the training stage of the subject. Both in a simple task such as filing (Person, 1960) and in a complex gymnastic motion of the knee circle mount (Kamon and Gormley, 1968) training causes substantial saving of energy so that the movement becomes more correctly timed with a reduction of overlapping activity within an agonist-antagonist pair and increase in the "sharpness" of activity of each involving muscle. Thus, although the subjects in the present study were in general well-trained, further special training of the take-off performance should be expected to improve their total performance level, on the average, at least by 8% (from 76—84%). In this way the take-off velocity of the total performance would correspond to 84% of that calculated from the segmental velocity maxima. Training should then reduce the time difference between the segmental velocity maxima to

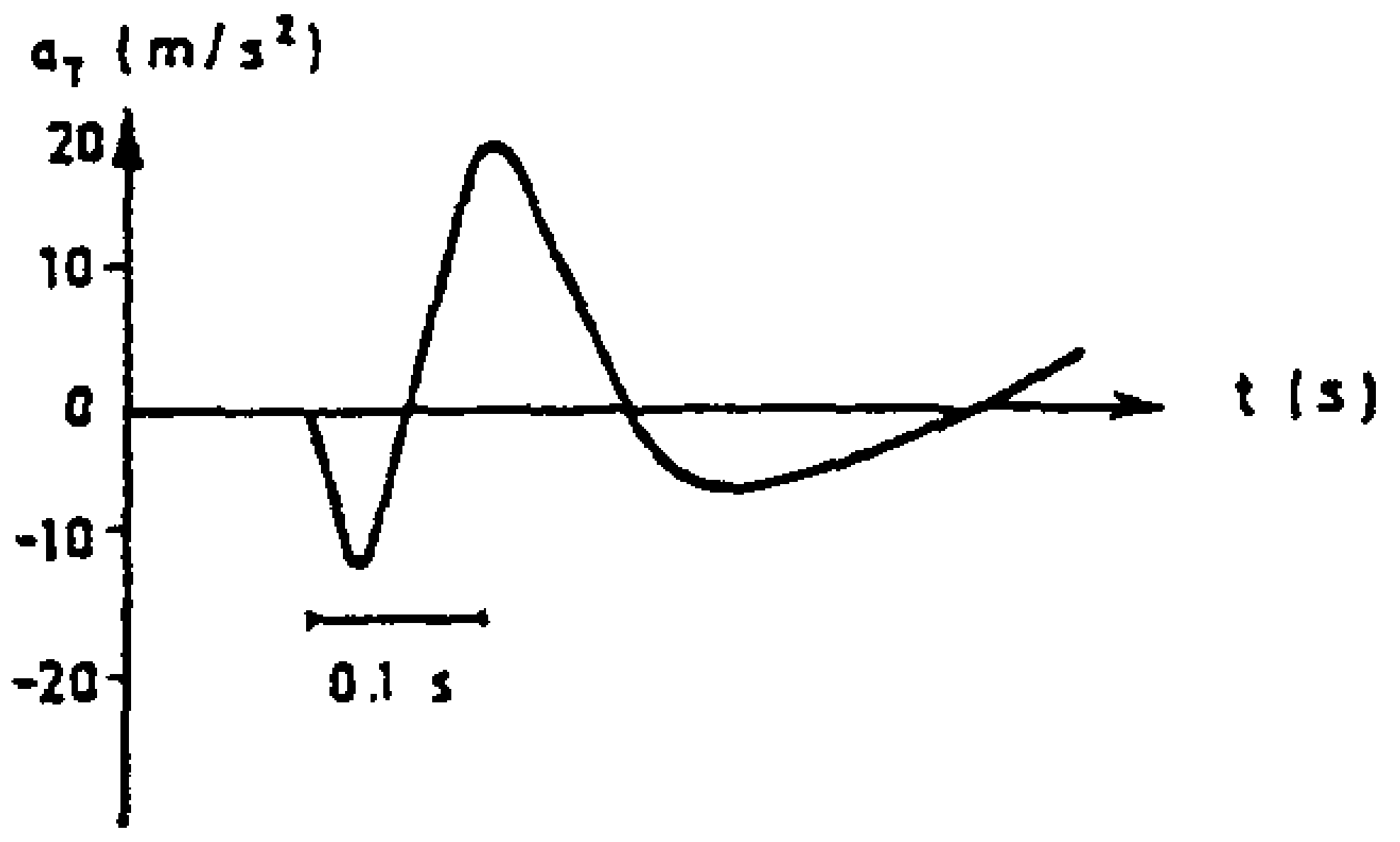

Fig. 5. An example of a maximum flexion movement performed from a fixed starting position (elbow angle 90°) of the forearm. Note the negative acceleration during the initiation of the movement. The subject was instructed to perform the rapid forearm flexion without countermovement

zero. Another possible source for explanation is the availability of neural energy for total performance.

Provided that the basic assumptions and the subsequent computations have been performed correctly in the present study, there still is, on the average, 16% difference in favor of the segmental performances. As is known from psychomotor studies (e.g., Michon, 1966) increase in the task complexity decreases the efficiency of the individual tasks. It has also been shown that the strength performance in two leg extension is approximately 87% of twice the average for one leg extension (Secher et al., 1976). Furthermore, Secher and coworkers gave indirect evidence, without verification of electromyographic measurements, of reduced motor unit activity during the two leg extension as compared to the one leg extension. Thus it is possible that similar inhibitory action on motor units might be a plausible cause for explaining the performance difference between the total motion and that calculated from the segmental velocity maxima. This certainly may open an interesting area for further investigation.

For each performance tested (Fig. 1), the subjects were instructed to exert the movement with maximal positive acceleration with no allowance for countermovement. Although no such countermovement could be observed in any of the analyzed performances, an attempt was made to quantify its possible existence with additional testing. Figure 5 shows a result of an example in which a skilled subject performed maximum elbow flexion movement from a fixed starting position. In this test a metal plate extending from the elbow to the finger tips was fastened on the forearm. An accelerometer (Brüel-Kjaer, type 4332) was placed on the plate to the point corresponding to the mass center of the forearm. Contrary to the instructions given, the maximum type positive work was always preceded by a short negative acceleration phase (countermovement). It is well-known that during pre-stretching a substantial amount of potential elastic energy can be stored in the muscle (e.g., Cavagna et al., 1968; Asmussen, 1974) and that this stored "extra" energy can be used during the positive work. Thus the possible existence of the elastic energy should be considered in the present study, although its different role in segmental vs. total performances cannot be estimated. The behavior of the muscle elastic components in these two kinds of performances is certainly worth of detailed investigation.

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