

## Storage of Elastic Energy in Skeletal Muscles in Man

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### Abstract

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The question, if muscles can absorb and temporarily store mechanical energy in the form of elastic energy for later re-use, was studied by having subjects perform maximal vertical jumps on a registering force-platform. The jumps were performed 1) from a semi-squatting position, 2) after a natural counter-movement from a standing position, or 3) in continuation of jumps down from heights of 0.23, 0.40, or 0.69 m. The heights of the jumps were calculated from the registered flight times. The maximum energy level,  $E_{neg}$ , of the jumpers prior to the upward movement in the jump, was considered to be zero in condition 1. In condition 2 it was calculated from the force-time record of the force-platform; and in condition 3 it was calculated from the height of the downward jump and the weight of the subject. The maximum energy level after take-off,  $E_{pos}$ , was calculated from the height of the jump and the jumper's weight. It was found that the height of the jump and  $E_{pos}$  increased with increasing amounts of  $E_{neg}$ , up to a certain level (jumping down from 0.40 m). The gains in  $E_{pos}$  over that in condition 1, were expressed as a percentage of  $E_{neg}$  and found to be 22.9 % in condition 2, and 13.2, 10.5, and 3.3 % in the three situations of condition 3. It is suggested that the elastic energy is stored in the active muscles, and it is demonstrated that the muscles of the legs are activated in the downward jumps before contact with the platform is established.

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The elastic properties of muscles have been known and studied extensively for many years. The original concept of *e.g.* Levin and Wyman (1927), *viz.* that the energy liberated at contraction was immediately stored as elastic energy in the series elastic components for subsequent use in performing work, has been abandoned, not least after the discovery of the "Fenn effect" (Fenn and Marsh 1935). Nevertheless muscle elasticity has continued to arouse the interest of muscle physiologists, and its possible role as a buffer and temporary store of mechanical energy has anew been brought to the attention of work physiologists *e.g.* by the studies of Cavagna *et al.* (1968). One way of investigating this possible function of the elastic component in muscle is to compare the release of external mechanical energy without and with a previous stretching of the involved muscles. This was done by Marey and Demeny (1885) who compared the heights of vertical jumps performed without and with a preliminary counter-movement and found the height to be higher in the latter case. Recently Cavagna *et al.* (1971) repeated these experiments, using a force-platform

Key words: elastic energy; negative work; vertical jump; force-platform.

with electronic registering, but they claimed to be unable to demonstrate a statistically significant difference in the two situations (see however later under Discussion).

It was, therefore, thought to be of interest to study the effect of a wider variation of energy implanted in the muscles during the preparatory movement preceding a jump. This was done by not only performing a counter-movement as Marey and Demeny, and Cavagna *et al.* did, but also by letting the subject jump down to the force-platform from levels of different heights.

## Material

The experimental data were collected from 19 young subjects, 14 males and 5 females. Their mean body weight was 71.0 kg (51.0 to 91.1 kg).

## Methods

A force-platform was constructed in such a way that the pressure registered by it was independent of the position of the subject on the platform (Bonde-Petersen 1974). The platform was slightly under-damped and had a natural frequency of about 50 Hz.

For registering of the pressures on the platform a Peekel 581 DHL strain-gauge bridge and amplifier was used. The signal, which was a linear function of the load within the applied range, was passed on to a Brush Mark 220 ink writer, operated at paper speed 125 mm/s.

In order to vary the energy level of the subject prior to the jump, 5 different situations were utilized. In one situation the subject jumped from a semi-squatting position. No preparatory counter-movement was allowed. In a second situation the subject was allowed a preparatory counter-movement, starting standing erect on the platform.

In the last three situations the subject jumped down from one of three different platforms, I to III, the heights of which were 0.233, 0.404 and 0.690 m, respectively, above the surface of the force-platform. The jump down was immediately, without stop, continued in the vertical upward jump. Examples of the records obtained during the jumps are shown in Fig. 1.

The height of the jump—*i.e.* the vertical lift of the subject's center of gravity—was calculated from the time of flight,  $t_f$  seconds, measured directly from the records (distance 4 to 5 in Fig. 1). This presupposes that the subject leaves and lands on the platform with the body held in the same position. The subjects, therefore, were instructed to keep the legs nearly extended at landing and to keep the arms at the sides with only slightly flexed elbows.

In the flight the subject will take off with a certain upward-directed velocity,  $v_f$  m/s, which will decrease and become zero at the apex of the jump. During the subsequent downward movement velocity will again increase and reach numerically the same value,  $v_f$  m/s, at touch-down. The time spent moving upwards or downwards will be the same and equal to  $\frac{1}{2} t_f$  s. As the acceleration of gravity is 9.81 m/s<sup>2</sup>, it follows that  $v_f = \frac{1}{2} t_f \times 9.81$  m/s.\* The average velocity, upwards or downwards, will be  $\frac{1}{2} v_f$  m/s or  $\frac{1}{4} t_f \times 9.81$  m/s. The distance,  $d$ , covered at this average velocity in the time  $\frac{1}{2} t_f$ —*i.e.* the height of the jump—will then be  $\frac{1}{4} t_f \times 9.81 \times \frac{1}{2} t_f = 1/8 (t_f)^2 \times 9.81$ , or  $d = 1.226 \times (t_f)^2$  m.

At the top of the flight the increase in energy level of the jumper over that in the position standing on the force-platform will then be  $w \times d$  kpm, in which  $w$  is the weight of the subject in kp.

Correspondingly, the increase in energy level of the subject at the moment he reaches the force-platform after jumping down from platforms I, II and III respectively (at point 1 in Fig. 1 C), can be calculated as  $w \times h$  kpm, in which  $w$  is the weight in kp of the subject and  $h$  is the height in m of platforms I—III.

In the case of jumping after a preparatory counter-movement (Fig. 1 B) the maximum increase in energy level of the subject, *i.e.* at point 2, is calculated as kinetic energy from  $E_{kin} = \frac{1}{2} mv^2$ . In this formula  $m$ , the inertial mass of the subject, equals weight divided by the acceleration of gravity *i.e.*  $w/9.81$ , and velocity,  $v$ , is calculated from  $F \times t = m \times v$ .

$F \times t$  ( $F$  = force,  $t$  = time) is measured planimetrically from the records (hatched area between 1 and 2 in Fig. 1 B).  $E_{kin}$  thus becomes  $(F \times t)^2 / 2w \times 9.81$  kpm.

\*  $v_f$  was also calculated from the registered force-time integral, using the formula  $F \times t = m \times v_f$ , in which  $F \times t$  was measured planimetrically. The two ways of calculating  $v_f$  gave identical results, showing that also dynamic forces applied to the platform were registered correctly.

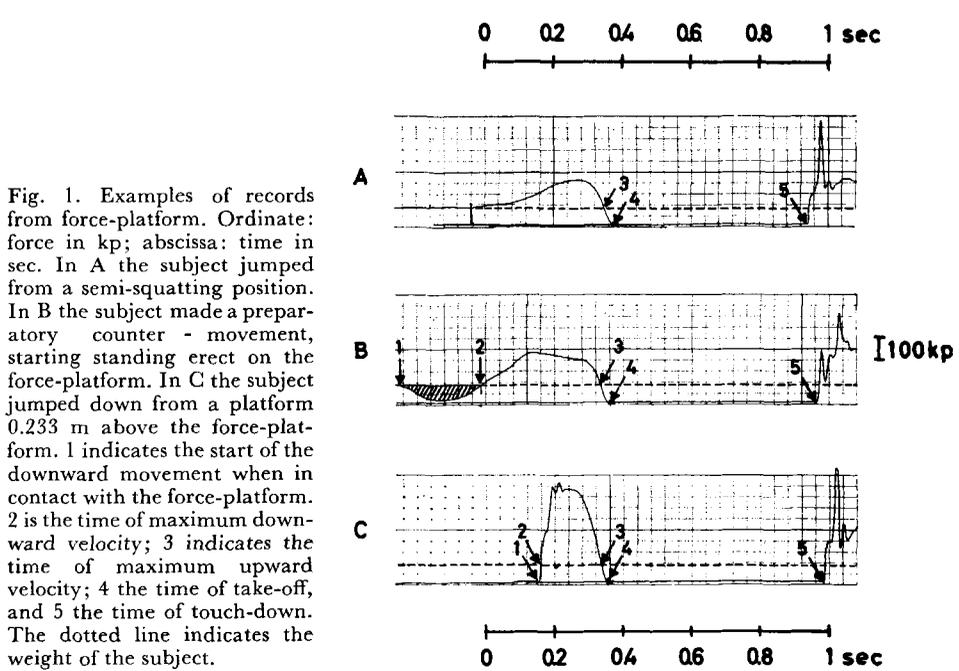


Fig. 1. Examples of records from force-platform. Ordinate: force in kp; abscissa: time in sec. In A the subject jumped from a semi-squatting position. In B the subject made a preparatory counter - movement, starting standing erect on the force-platform. In C the subject jumped down from a platform 0.233 m above the force-platform. 1 indicates the start of the downward movement when in contact with the force-platform. 2 is the time of maximum downward velocity; 3 indicates the time of maximum upward velocity; 4 the time of take-off, and 5 the time of touch-down. The dotted line indicates the weight of the subject.

TABLE I. Height of vertical jump 'd' in m, calculated from the time of flight (see text) without or with preparatory movements.

subject		after jumping down from platforms I - III				
no., sex	body weight kp	from squatting position	with a counter-movement	I, height 0.233 m	II, height 0.404 m	III, height 0.690 m
1 m.	75.8	0.450	0.515	0.515	0.515	0.491
2 m.	87.5	0.316	0.307	0.320	0.307	0.345
3 m.	70.1	0.320	0.358	0.372	0.394	0.404
4 m.	61.5	0.485	0.519	0.538	0.555	0.557
5 m.	70.0	0.444	0.484	0.495	0.529	0.473
6 m.	73.6	0.356	0.342	0.340	0.354	0.357
7 m.	69.7	0.443	0.408	0.441	0.429	0.442
8 m.	79.1	0.340	0.392	0.399	0.432	0.356
9 m.	79.4	0.342	0.370	0.399	0.386	0.372
10 m.	91.1	0.466	0.503	0.470	0.473	0.470
11 m.	83.5	0.399	0.413	0.413	0.424	0.412
12 f.	57.6	0.323	0.351	0.350	0.388	0.301
13 m.	71.0	0.366	0.448	0.486	0.517	0.473
14 f.	59.6	0.218	0.215	0.228	0.245	0.206
15 f.	62.6	0.323	0.304	0.311	0.307	0.298
16 m.	72.0	0.370	0.355	0.349	0.386	0.396
17 m.	74.0	0.410	0.401	0.425	0.442	0.384
18 f.	59.1	0.250	0.269	0.277	0.280	0.253
19 f.	51.0	0.340	0.381	0.389	0.403	0.410
$\bar{X}$	71.0	0.366	0.386	0.396	0.408	0.389
SD	—	0.071	0.083	0.083	0.086	0.086
SE	—	0.016	0.019	0.019	0.019	0.019

TABLE II. Maximum energy levels at start ( $E_{neg}$ ) and end ( $E_{pos}$ ) of the period preceding the take-off.  $\Delta kpm$  indicates the gain in  $E_{pos}$  for each jumping condition over  $E_{pos}$  during the jump from the squatting position. In the last column  $\Delta kpm$  is expressed in per cent of  $E_{neg}$ .

jumping condition	$E_{neg}$ kpm	$E_{pos}$ kpm	$\Delta kpm$	$\frac{\Delta kpm \times 100}{E_{neg}}$ %
squatting	0	26.0	—	—
counter-movement	6.1	27.4	1.4	22.9
I, height 0.233 m	16.6	28.2	2.2	13.2
II, height 0.404 m	28.7	29.0	3.0	10.5
III, height 0.690 m	49.0	27.6	1.6	3.3

### Results

The individual results of jumping from a squatting position, with a counter-movement, or after jumping down from heights I—III are shown in Table I. The table shows that the height of the jump,  $d$ , becomes increasingly greater if a counter-movement or a jump down from a height precedes the actual jump—but only up to height II (0.40 m). After jumping down from height III (0.69 m),  $d$  again becomes smaller, although still greater than when jumping from a squatting position.

These differences are all statistically significant at a 0.02 level. (Student's  $t$ -test, paired samples).

The energy levels of the subjects (averages of all only) are calculated as described in Methods and tabulated in Table II. In this Table  $E_{neg}$  signifies the highest level of energy in the downward movement before the jump. In jumping from a squatting position  $E_{neg}$  has the value of zero.  $E_{pos}$  correspondingly signifies the highest energy level reached during the upward movement. The Table shows that the energy is 26.0 kpm when jumping from a squatting position and increases stepwise up to 29.0 kpm with increasing steps of  $E_{neg}$  preceding the jump. At the highest level of  $E_{neg}$ , however, this trend is reversed and  $E_{pos}$  becomes smaller again. The gain in  $E_{pos}$ ,  $\Delta kpm$ , over  $E_{pos}$  from the jumps from the squatting position is shown in the Table, also as a percentage of the corresponding value of  $E_{neg}$ .

### Discussion

In jumping from the squatting position (Fig. 1 A) it must be assumed that the subjects exerted themselves maximally right from the start of the jump. The recorded force, however, rose very slowly and the maximum was not reached until after about 300 ms. The reason for this probably is that a certain amount of the liberated energy was wasted in taking up the slack and stretching the elastic components of the muscles (*cf.* Hill 1970). In human muscles it has been demonstrated, a.o. by Asmussen and Sørensen (1971). When a counter-movement was performed before the jump (Fig. 1 B), a certain amount of energy,  $E_{neg}$ , was implanted into the body in excess

of the energy liberated by the muscle contractions, which again are assumed to be maximal. Part of this must have degenerated into heat, but another part most probably was absorbed by the elastic components of the muscles, so that less of the energy subsequently liberated by the muscles was wasted as internal work. As a consequence more energy was available for external work, resulting in a greater height of the jump.  $E_{\text{pos}}$  was increased by a value that represents about 23 % of  $E_{\text{neg}}$  (Table II).

When the subjects jumped down from heights I—III, respectively, still more energy was made available for tautening and stretching the elastic components (Table II). More energy could, therefore, be made useful for the jump. The highest increase in  $E_{\text{pos}}$  over that gained in a jump from a squatting position was on an average 3.0 kpm. Inspection of Table I shows, though, that several individuals gained even more, subject no. 13 for instance 10.7 kpm when jumping from height II. That is 37.7 % of the implanted  $E_{\text{neg}}$ . Others, on the other hand, gained nothing, some even performing worse when jumping down from a height (e.g. subject no. 15). Fig. 1 C illustrates how the maximum tension typically is 2—3 times as large as in situation A. It is, therefore, justifiable to assume that the elastic components not only were stretched corresponding to the maximum tension that can be developed voluntarily by the contractile mechanism, but that a certain tension above that was produced temporarily by the rapid stretching of the elastic components by gravity. This tension was liberated immediately thereafter, adding to the amount of energy provided by the contractile mechanism. Such high tensions (3—400 kp) should not astonish as we know that strong persons can produce tensions of up to 1000 kp as isometric contractions with their leg extensor muscles.

It will be noticed from Table II, comparing height I to height II that the increase in  $E_{\text{neg}}$  of  $28.7 - 16.6 = 12.1$  kpm, was accompanied by an increase in  $E_{\text{pos}}$  of  $29.0 - 28.2 = 0.8$  kpm, *i.e.* a net gain as  $E_{\text{pos}}$  of 6.6 % of the extra  $E_{\text{neg}}$ . The two situations were, technically, alike, and directly comparable. The most likely explanation would also here be that these 6.6 % were energy transferred from  $E_{\text{neg}}$  to  $E_{\text{pos}}$  via stored elastic energy. The situation is similar to the one studied by Asmussen and Sørensen (1971), where a maximal eccentric muscle contraction was continued without relaxation as a maximal concentric contraction. Depending on the speed of movement a considerable gain in work could be achieved—up to 70 % for the very first part of an arm flexion at high speed.

Increasing the height of the downward jump from 0.40 m to 0.69 m—*i.e.*  $E_{\text{neg}}$  from 28.7 kpm to 49.0 kpm—was not followed by a further increase in 'd' or in  $E_{\text{pos}}$ , but rather by a decrease. The reason for this is probably that the forces developed during the braking of the fast downward movement were so great that they might endanger the jumpers, who consequently did not exert themselves maximally. Whether this decrease in  $\Delta E_{\text{pos}}$  was due to a conscious or to a reflex inhibition cannot be decided.

A prerequisite for the explanation given above is that the structures that absorb the negative energy from the counter-movements possess such properties that they

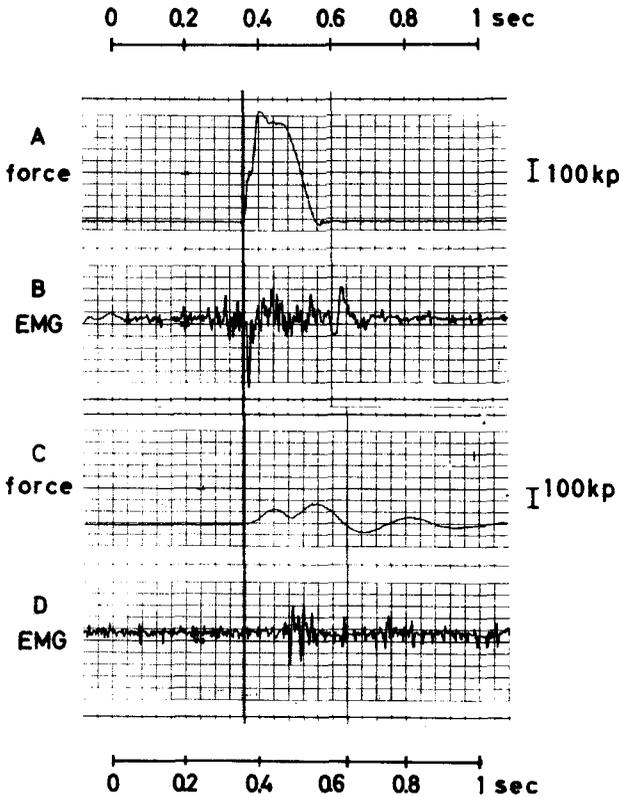


Fig. 2. The record from the force-platform (A and C) and the EMG (arbitrary units) from the soleus muscle (B and D) during two different procedures. In A and B simultaneous records were obtained as the subject jumped down from a height of 0.404 m., continuing in a maximal vertical jump. C and D were simultaneously recorded as a sudden pressure was applied vertically downward to the shoulders of the subject standing tip-toes on the force-platform.

are able to store appreciable amounts of elastic energy—*i.e.* they must show a high degree of elastic stiffness. As already Fenn (1930) pointed out, resting muscles can be dismissed from consideration because of their very low stiffness in the physiological range of movement. Active muscles, on the other hand, have a much higher degree of stiffness within the same range (Buchthal and Kaiser 1951, p. 96, Fig. 41). It would accordingly be very unlikely, if the muscles of the legs in the present experiments were not active at the moment of touch-down (*cf.* Fig. 1 C).

In order to prove this, electromyographic records were obtained by means of a Disa electromyograph connected to the Brush ink-writer, and surface electrodes, glued to the skin over the soleus muscle and the vastus lateralis muscle. Fig. 2 A–B shows the EMG from the soleus and the record from the force-platform when a subject jumped down from a height of 0.404 m preliminary to a vertical jump. It is obvious that the touch-down was preceded by an increased electrical activity of the soleus—due to an anticipatory increase in muscle tone beginning about 100 ms before contact with the force-platform was made (*cf.* Melvill Jones and Watt 1971). A simple myotatic reflex, elicited by the stretching of the muscles at landing, would be too slow for counteracting the fall. Fig. 2 C–D shows how a sudden downward pressure applied to the shoulders of the subject, standing on tip-toes on the force-platform,

elicited a reflex in the soleus muscles. This is demonstrated by the increased electrical activity (Fig. 2 D), and by the subsequent oscillations in the record from the force-platform (Fig. 2 C). The reflex time was about 120 ms, *i.e.* more than half the time spent in contact with the platform in a jump (Fig. 2 A) (*cf.* also Grillner 1972).

It may be argued that even though the whole muscle—*in casu* soleus—is active during the time of energy absorption—*i.e.* from touch-down to the start of the upward movement—its individual muscle fibers may pass through periods of relaxation in which all stored elastic energy would be lost. A voluntary contraction of a whole muscle is the result of the summated contractions of numerous muscle fibers, some of which may perform series of single twitches while others may be tetanized—all depending on the natural frequencies of the nervous impulses to the muscle. But even in the former case the duration of a single twitch is so long ( $74 \pm 11$  ms for the “time to crest” in the soleus muscle according to Buchthal and Schmalbruch 1970) that it covers an appreciable part of the negative phase in the jump. The duration of the negative phase,  $t_x$ , of the jump, while in contact with the force-platform can be estimated from the following arguments:

Let the *downward movement*, from touch-down to the movement has been completely stopped, last  $t_x$  s, have an initial velocity of  $v_h$ , a final velocity of zero and an average velocity, therefore, of  $\frac{1}{2}v_h$  m/s. The distance covered in this movement will then be  $t_x \times \frac{1}{2}v_h$ . Calling the total time of contact with the force-platform (point 1 to point 4 in Fig. 1 C)  $t_{tot}$  the subsequent *upward movement* on the platform will last  $(t_{tot} - t_x)$  s. The initial velocity will be zero, the final velocity,  $v_{fin}$ , and, therefore, the mean velocity  $\frac{1}{2}v_{fin}$ . The distance covered in this movement must be the same as in the downward movement, hence

$$t_x \times \frac{1}{2}v_h = (t_{tot} - t_x) \frac{1}{2}v_{fin}, \text{ and, solving for } t_x$$

$$t_x = (v_{fin} \times t_{tot}) / (v_h + v_{fin})$$

$v_{fin}$  is calculated from the height of the jump ( $h = \frac{1}{2}(v_{fin}^2/g)$ );  $v_h$  correspondingly from the height from which the subject jumped down, and  $t_{tot}$  is measured on the record from the force-platform, from touch-down to take-off (1 to 4 in Fig. 1 C). In the case of the counter-movement,  $v_h$  is determined as described under  $E_{neg}$ .

Calculated in this way the average values  $\pm$ S.D. for  $t_x$ —the durations of the negative phase during which the possible storing of elastic energy takes place—were found to be 0.268 s after the counter-movement, and  $0.190 \pm 0.064$ ,  $0.162 \pm 0.056$ , and  $0.141 \pm 0.047$  s after jumping down from heights 0.233, 0.404 and 0.690 m, respectively.

Accordingly, the active period even of single twitches, determined as “time to crest” by Buchthal and Schmalbruch (1970) occupies one half to one third of the negative phase of the jumps and thus provides good opportunities for storing of energy in stiff muscle fibers.

Our results have shown that a phase of negative work, preceding the jump, significantly increases the jumping height, up to a certain limit. This confirms the results of Marey and Demeny (1885). Cavagna *et al.* (1971) calculated from their experiments that such an enhancement was not demonstrable at a statistically significant level. However, a Student's-t-test performed on the data of Cavagna

*et al.* reveals that a counter-movement *de facto* results in a significant increase in the velocity of take-off of 6.4 % ( $P < 0.01$ ), corresponding to an increase in height or  $E_{\text{pos}}$  of 11.3 %, *i.e.* twice the average increase in our data (*cf.* Table I).

The possible storage of elastic energy in muscles under other conditions (*e.g.* running and walking) has recently attracted renewed attention (Cavagna *et al.* 1964, 1971, Lloyd and Zacks 1972, Grillner 1972). The present experiments should add to the understanding of the importance of storage of elastic energy in the contracted muscle during eccentric conditions as a mediator for increasing the total work output during short bursts of muscle activity.

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