

Utilization of stored elastic energy in leg extensor muscles by men and women

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ABSTRACT

KOMI, PAAVO V., AND CARMELO BOSCO. Utilization of stored elastic energy in leg extensor muscles by men and women. *Med. Sci. Sports*. Vol. 10, No. 4, pp. 261-265, 1978. An alternating cycle of eccentric-concentric contractions in locomotion represents a sequence when storage and utilization of elastic energy takes place. It is possible that this storage capacity and its utilization depends on the imposed stretch loads in activated muscles, and that sex differences may be present in these phenomena. To investigate these assumed differences, subjects from both sexes and of good physical condition performed vertical jumps on the force-platform from the following experimental conditions: squatting jump (SJ) from a static starting position; counter-movement jump (CMJ) from a free standing position and with a preparatory counter-movement; drop jumps (DJ) from the various heights (20 to 100 cm) on to the platform followed immediately by a vertical jump. In all subjects the SJ, in which condition no appreciable storage of elastic energy takes place, produced the lowest height of rise of the whole body center of gravity (C.G.). The stretch load (drop height) influenced the performance so that height of rise of C. of G. increased when the drop height increased from 26 up to 62 cm (males) and from 20 to 50 cm (females). In all jumping conditions the men jumped higher than the women. However, examination of the utilization of elastic energy indicated that in CMJ the female subjects were able to utilize most ($\approx 90\%$) of the energy produced in the prestretching phase. Similarly, in DJ the overall change in positive energy over SJ condition was higher in women as compared to men. Thus the results suggest that although the leg extensor muscles of the men subjects could sustain much higher stretch loads, the females may be able to utilize a greater portion of the stored elastic energy in jumping activities.

POSITIVE AND NEGATIVE WORK, ELASTIC ENERGY, MUSCLE MECHANICS

In human muscular work two types of contractions are primarily utilized: concentric and eccentric. Often these contractions take place in an alternating cycle so that the eccentric phase precedes the concentric one. In this type of sequence it has been demonstrated that during the eccentric contraction a substantial amount of potential energy can be stored in the stretched muscle. This energy can, in turn, be partly recovered in the subsequent concentric contraction. A vertical jump performed with a preceding counter-movement or a jump down from platforms of 30 to 70 cm high represents an activity in which this storage and utilization of elastic energy can be demonstrated

(1). This study was designed to further examine the performance in vertical jump by imposing different stretch loads on activated leg extensor muscles. It was also thought that this technique might be of use to investigate the possible differences in the storage capacity and utilization of elastic energy between men and women of comparable physical condition.

METHODS

Subjects. Fifty-seven subjects participated in the study. They were divided in three groups as follows: female physical education students ($n = 25$), male physical education students ($n = 16$), and players from the Finnish national men's volleyball team ($n = 16$). Table 1 gives the physical characteristics of the subjects.

Jump performances. Techniques similar to those introduced by Asmussen and Bonde-Petersen (1) were used in the various jump performances. Each subject performed vertical jumps on the force-platform with the following different initial starting positions: (1) Squatting position in which no preparatory counter-movement was allowed. This performance is called a jump from a maintained (90° knee angle) static position (SJ); (2) from erect standing with allowance for counter-movement, called jump with counter-movement (CMJ); (3) from erect standing on different elevations and then dropping directly on the force-platform with subsequent jump upwards. This condition is called a drop-jump (DJ). The dropping heights were varied from 20 to 100 cm.

In all test conditions the subjects kept their hands on the hips. This was necessary to control that the landing position on the platform approached that of takeoff. In order

TABLE 1. Physical characteristics of the subject groups. The values indicate the mean \pm S.D.

Group	N	Age (years)	Weight (kg)	Height (cm)
WOMEN physical education students	25	20.6 ± 1.2	58.2 ± 5.6	165.6 ± 6.0
MEN physical education students	16	24.0 ± 1.4	75.4 ± 11.2	176.7 ± 8.3
MEN volleyball players	16	24.0 ± 3.5	82.8 ± 7.9	185.8 ± 6.7

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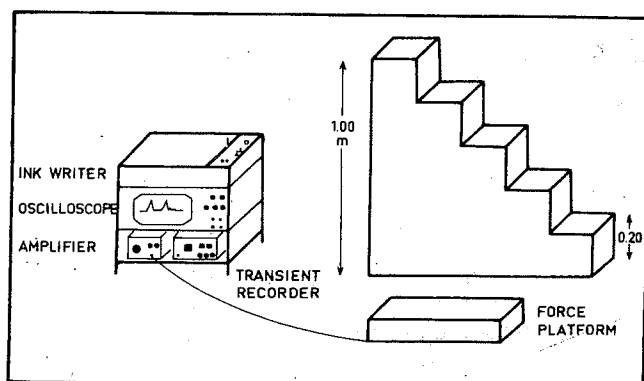


Figure 1—Schematic presentation of the stair platform for drop-jumps and the force-platform with its instruments for recording the vertical ground reaction force.

to minimize horizontal and lateral displacement during the jump the subjects were also instructed that the points of takeoff and landing on the platform were approximately the same.

Instrumentation. Figure 1 gives a schematic presentation of the instrumentation used in the study. The force-platform (6) recorded the vertical ground reaction force with four Kyowa LCP 500 KA transducers. After amplification the signal was passed through a transient recorder (Transient Store Model 512A) for immediate display of the total force-time curve on the oscilloscope, and for subsequent drawing on the inkwriter. Figure 1 also shows the stairplatform from which the different DJ's took place. In the early part of the experiment the dropping heights were arranged with wooden blocks. Thus the drop increments were not always 20 cm. as shown in Figure 1.

CALCULATIONS

Figure 2 shows examples of the force-time curves in three jumping conditions. By measuring the flight time (t_{air}) from the record, one can calculate the vertical takeoff velocity (V_i) of the center of gravity as follows:

$$V_i = 1/2 \times t_{air} \times g \quad [1]$$

in which g = acceleration of gravity (9.81 m/s^2)

The height of rise (h) of the center of gravity can then be computed:

$$h = \frac{V_i^2}{2 \times g} \quad [2]$$

This method of calculation assumes that the positions of the jumper on the platform were the same in takeoff and landing. To observe the possible errors in the calculations, six different jumps were also filmed with a LoCam 51-0003 16 mm camera set to operate at 100 frames per second. The location of the whole body center of gravity was computed from the film on Vanguard analyzer using Dempster's (1955) model for the body segment parameters. Comparison of the displacement data gave an error of ± 2.0 percent for the computation from the platform.

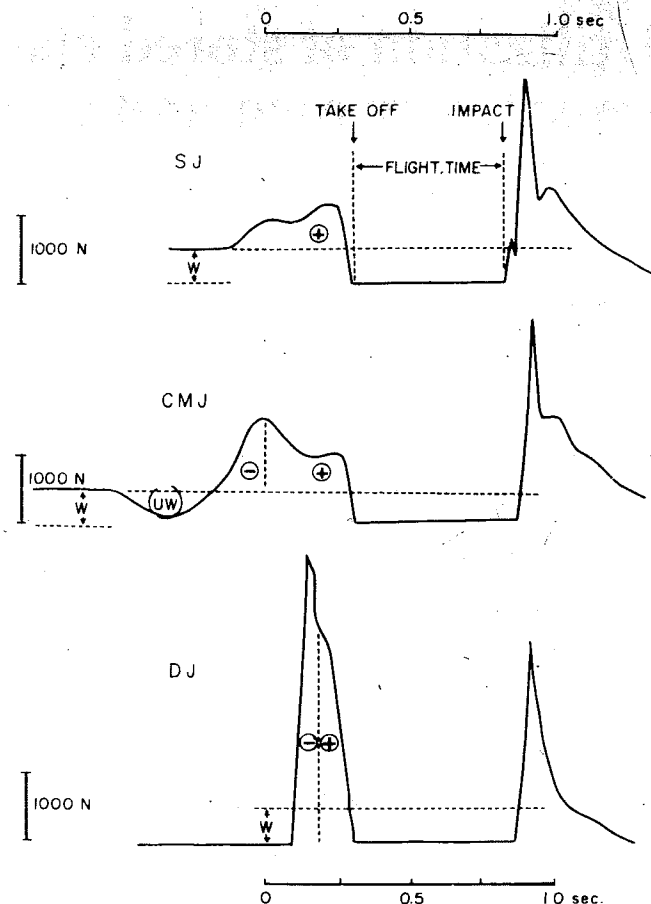


Figure 2—Examples of force-time curves of the vertical ground reaction force in the three different jumping conditions: squatting jump (SJ), counter-movement jump (CMJ), and drop-jump (DJ). Other symbols: w = weight of the subject; UW = unweighting phase in CMJ; \ominus = phase of deceleration in eccentric (negative) work, during which period the center of gravity is still moving downwards and the storage of elastic energy is assumed to take place; \oplus = phase of concentric (positive) work during which the center of gravity moves upwards.

To compare the maximum increases in positive (E_{pos}) and negative (E_{neg}) energy levels in the different jump conditions, the kinetic energy (E_{kin}) acquired by the subject was computed using the formula:

$$E_{kin} = 1/2 m V^2 \quad [3]$$

in which m = mass (in kg) of the subject

V = vertical takeoff velocity

To apply this formula (3) for obtaining the maximum increase in downward energy level (E_{neg}) in CMJ-condition, the maximum downward velocity was first computed by integrating the area under the unweighting phase of the curve (UW of Figure 2):

$$\int_0^t F(t) dt = m \times V \quad [4]$$

in which F = force

t = time

In DJ conditions, the corresponding maximum downward velocity was calculated utilizing formula (2):

$$V = \sqrt{2gh}$$

in which case h = dropping height.

TABLE 2. Mean values (\pm S.D.) of the maximum height (in cm) of the center of gravity under the different jumping conditions.

Jumping Condition	WOMEN physical education students	MEN physical education students	MEN volleyball players
Squatting (SJ)	19.2 \pm 3.6	35.5 \pm 5.1	37.2 \pm 3.7
Counter-movement (CMJ)	23.3 \pm 3.5	40.3 \pm 6.6	43.4 \pm 5.2
*Drop-jump (DJ)	27.3 \pm 3.6 (47.6 \pm 19.4)	40.3 \pm 6.9 (63.0 \pm 22.7)	41.1 \pm 4.5 (66.0 \pm 16.3)

*The drop-jumps were performed from different heights ranging from 20 to 100 cm. In this condition, the value in parentheses denotes the corresponding average dropping height which gave the highest performance.

TABLE 3. Maximum energy levels in the beginning (E_{neg}) and at the end (E_{pos}) of the period prior to takeoff.

Jumping Condition	E_{neg} (J)	E_{pos} (J)	ΔE_{pos} (J)	$\frac{\Delta E_{pos} \times 100\%}{E_{neg}}$
FEMALE SUBJECTS				
Squatting (S)	0	111.2	—	—
Counter-movement (CMJ)	25.1	134.2	23.0	91.6
Drop-jumps (DJ)				
/20 cm	114.1	137.6	26.4	23.1
/30 cm	171.1	144.5	33.3	19.5
/40 cm	222.3	146.4	35.2	15.8
/50 cm	285.5	147.2	36.0	12.6
/60 cm	342.2	139.5	28.4	8.3
/70 cm	395.3	134.6	23.4	5.9
/80 cm	460.9	131.5	20.3	4.4
**Best drop-jump (average — 47.6 cm)	(271.8)	(155.9)	(44.7)	(16.4)
MEN PHYSICAL EDUCATION STUDENTS				
Squatting (S)	0	262.4	—	—
Counter-movement (CMJ)	72.8	297.9	35.5	48.8
Drop-jumps (DJ)				
/26 cm	192.2	267.6	5.2	2.7
/45 cm	332.6	280.9	18.5	5.6
/62 cm	458.0	284.6	22.2	4.8
/83 cm	613.5	280.1	17.7	2.9
**Best drop-jump (average — 63 cm)	(465.7)	(297.9)	(35.5)	(5.5)
MEN VOLLEYBALL PLAYERS				
Squatting (S)	0	301.9	—	—
Counter-movement (CMJ)	100.7	352.2	50.3	50.0
Drop-jumps (DJ)				
/26 cm	210.9	305.9	4.0	1.9
/45 cm	365.2	309.8	7.9	2.2
/62 cm	503.4	325.4	23.5	4.7
/83 cm	673.5	313.2	11.3	1.7
**Best drop-jump (average — 66 cm)	(535.9)	(333.8)	(31.9)	(5.9)

* ΔE_{pos} signifies the gain in E_{pos} in the different conditions as compared to E_{pos} in squatting.

**Best drop-jump signifies the mean of these dropping heights in which the individual performances were highest.

RESULTS

Group comparison. The average values of the maximum height jumped from the three experimental conditions are shown in Table 2. The table shows that the results of the female students differed substantially from the two male groups. In general, their performances were from 54 to 67 percent below that of their male counterparts. The volleyball players, on the other hand, reached the performance level which was two to eight percent higher than that of the male physical education students.

Comparison between the jump conditions. In all groups, SJ was significantly ($p < .01$) the least efficient condition as compared to the performance in CMJ or DJ's.

These two latter conditions showed no significant difference in performance in any of the groups studied.

The dropping height of DJ's influenced performance in all groups studied. In males, the height of rise of center of gravity increased when the drop height was increased from 26 up to 62 cm. Similarly, the female subjects showed increases from 20 up to 50 cm.

Energy levels during the different jump conditions. The calculations of the average maximum energy levels in the three groups are given in Table 3. E_{neg} is zero in SJ and increases in all groups in CMJ and further in DJ's. E_{pos} , in females, showed a low value of 111.2 J in SJ condition, but then increased in other conditions so that it was highest

(147.2 J) in DJ from 50 cm height. In men subjects, however, CMJ gave the highest E_{pos} values of 297.9 J and 352.2 J, respectively for physical education students and volleyball players. Correspondingly, the gain in positive energy (ΔJ) over the SJ was for girls highest in DJ/50 cm, and for men in CMJ. If the gain is expressed in percent of E_{neg} (the right hand column in Table 3), then CMJ gives the highest values for all groups. In this condition utilization of elastic energy was 91.6% and 48.8 – 50.0%, respectively, for female and male subjects.

DISCUSSION

In the three conditions of the present study – squatting jump (SJ), counter-movement jump (CMJ) and drop-jumps (DJ) – different stretch loads were given to the leg extensor muscles prior to the positive phase of the vertical jump. The involvement of the arms was eliminated by instructing the subjects to keep their hands on the hips during the entire performance. The contribution of the arms to the vertical jump may be 10% or more (8). The position of the upper body was also standardized so that a minimum of flexion and extension of the trunk occurred. Thus, it is believed that the leg extensors were the main contributors to the performance in the different jumps of the study.

The results of the present study clearly demonstrated that the men subjects had much better performance than the women subjects in all the experimental conditions. This is an expected finding and it is in accordance with the general differences between men and women in strength-speed type performance (7). However, a question arises whether the obtained results are indicative of any difference between men and women subjects as regards the storage and utilization of elastic energy.

In light of the obtained results, this comparison in the storage and utilization of elastic energy can be investigated from two different viewpoints. First, examination of the gains in E_{pos} (ΔJ) in CMJ over SJ indicates that the women subjects had higher relative increase in E_{pos} (23.0 J = 21%) than the men subjects (35.5 J = 13.5%; 50.3 J = 17%, respectively, for physical education students and volleyball players). If these changes in E_{pos} are expressed in percent of E_{neg} (last column in Table 3), we can state that the women were able to utilize most (= 90%) of the energy absorbed in the stretching phase (E_{neg}) of the CMJ condition. This portion is much higher than that of the men groups (49% and 50%, respectively).

Another way of comparison is to examine the maximum energy levels in the different DJ's. In all groups E_{pos} and consequently, the height of rise of center of gravity, increased when the dropping height was increased (Table 3 and Figure 3). In contrast to women, the men were able to improve their performance from much higher drops, in which cases the stretch loads and E_{neg} values are much higher. However, this overall change in E_{pos} from the SJ condition in men subjects was both absolutely and relatively much smaller than in women in almost all DJ con-

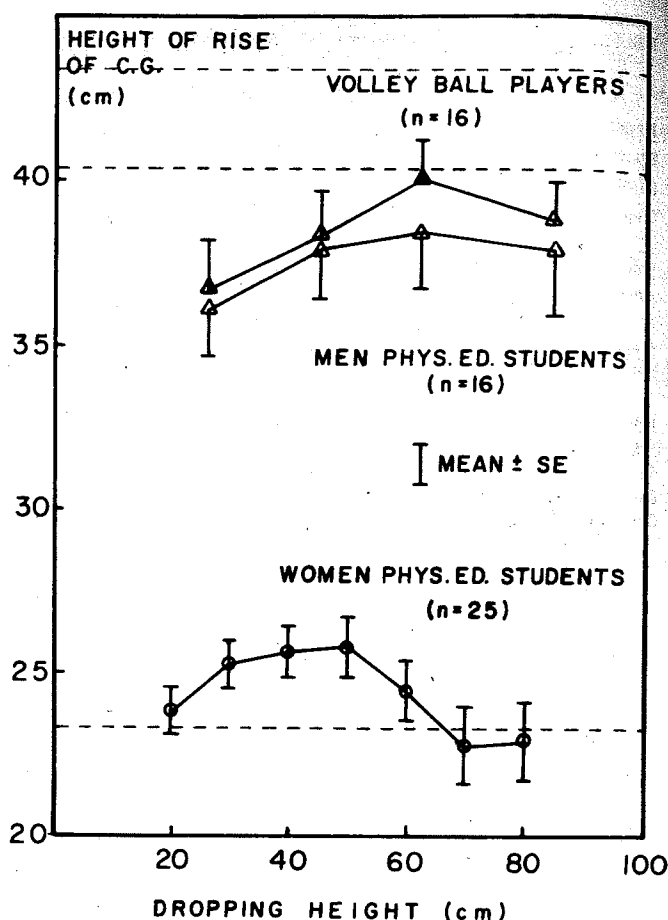


Figure 3—Group comparison of the height of rise of the total body center of gravity in vertical jumps performed immediately after dropping on the platform from different heights. The dashed lines represent the average values in CMJ; top: volleyball players; middle: men students; below: women students.

ditions. This is also evident from Figure 4, which compares the net gains in E_{pos} over E_{neg} . The absolute difference is additionally surprising because the mass term in formula $1/2 mV^2$ to calculate E_{kin} is smaller in females as compared to males.

It may be argued against these comparisons by speculating that the women subjects in the present study did not perform up to their maximum in SJ, especially if the comparison is made with the female subjects of Asmussen and Bonde-Petersen (1). Our subjects were, however, instructed to put their very best effort in all jump conditions. Computation of ΔE_{pos} assumes that performance was always maximal including SJ. It can also be speculated that the observed sex difference in utilizing the potential elastic energy may be due to the difference in body dimensions between men and women. It could be thought that the smaller dimensions of the female subjects would make them better for utilization of elastic energy. It seems, however, that this speculation is not valid because our recent experiments (Bosco & Komi, in preparation) with boys and girls of the similar body dimensions gave results compa-

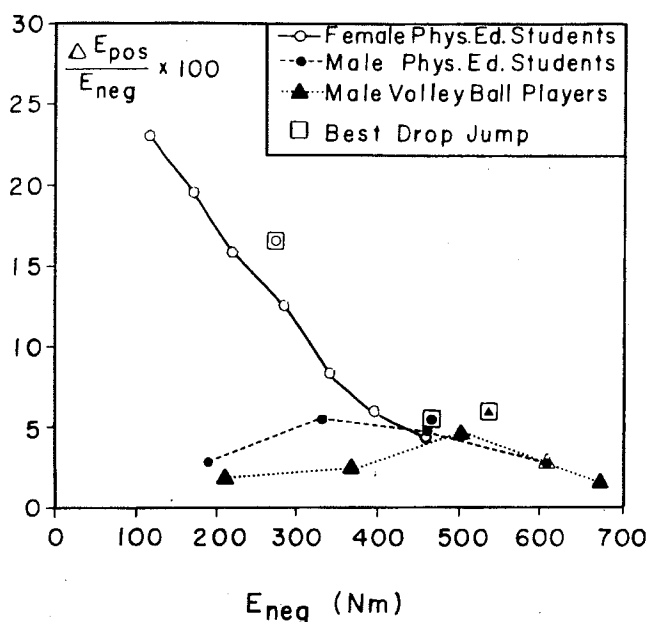


Figure 4—Group comparison in the utilization of the stored elastic energy ($\frac{\Delta E_{pos}}{E_{neg}} \times 100$) in vertical drop jumps of different stretch energy loads (E_{neg}).

able to the present study. Thus the obtained results indicate that men subjects in good physical condition can sustain much higher stretch loads than their female counterparts. However, they also suggest strongly that the females as compared to males are able to utilize a greater portion of the stored elastic energy both in CMJ and DJ conditions of the study (Figure 4).

In contrast to females our male subjects demonstrated almost equal performances in CMJ and DJ conditions. This is contrary to the finding of Asmussen and Bonde-Petersen (1), whose subjects had their best jumps in DJ of 41 cm. It is important to note this difference, but it may be due to differences in the initial unweighting phase of CMJ. As Cavagna et al. (3) have observed for human elbow flexors, the velocity of the stretch load determined how much storage and utilization of elastic energy can take place. Now it may be speculated that the stretching of active muscles immediately following the initial unweighting phase took

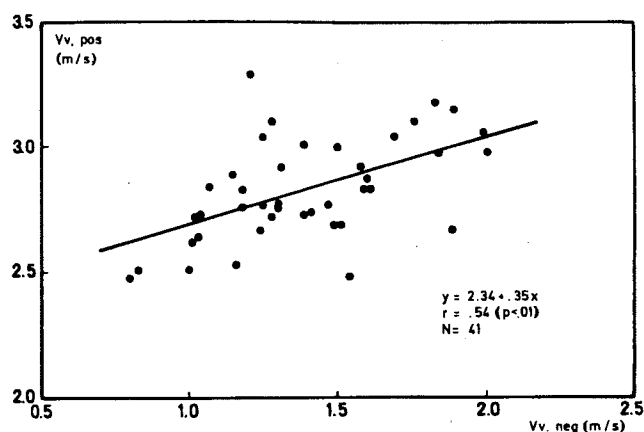


Figure 5—Comparison between the takeoff velocity ($V_{v, pos}$) and the maximum downward velocity ($V_{v, neg}$) in counter-movement jump of all subjects.

place faster in our subjects (e.g. $V_{v, neg} = 1.56$ m/sec for volleyball players). That the rate of stretch influences the final result, also in vertical jump, is demonstrated in Figure 5, which shows a significant linear relationship between $V_{v, neg}$ and $V_{v, pos}$ for all subjects.

It must also be pointed out that our results for men are in good agreement with those of Cavagna et al. (4), who observed an average ΔE_{pos} of 13% in CMJ over SJ. Calculation of corresponding figures from Table 3 give 13% and 16.7%, respectively, for men physical education students and volleyball players.

The earlier work of Cavagna et al. (2) on isolated muscle preparation can be used to explain the storage and utilization of elastic energy in CMJ and DJ conditions of the present study. However, the superiority of the females over the male subjects in utilizing the stored elastic energy is puzzling and cannot be explained at the present state of these studies in progress.

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