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Biomechanical analysis of drop and countermovement jumps

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Summary. For 13 subjects the performance of drop jumps from a height of 40 cm (DJ) and of countermovement jumps (CMJ) was analysed and compared. From force plate and cine data biomechanical variables including forces, moments, power output and amount of work done were calculated for hip, knee and ankle joints. In addition, electromyograms were recorded from five muscles in the lower extremity. The results obtained for DJ appeared to depend on jumping style. In a subgroup of subjects making a movement of large amplitude (i.e. bending their hips and knees considerably before pushing off) the push-off phase of DJ closely resembled that of CMJ. In a subgroup of subjects making a movement of small amplitude, however, the duration of the push-off phase was shorter, values for moments and mean power output at the knees and ankles were larger, and the mean EMG activity of m. gastrocnemius was higher in DJ than in CMJ. The findings are attributed to the influences of the rapid pre-stretch of knee extensors and plantar flexors after touch-down in DJ. In both subgroups, larger peak resultant reaction forces were found at the knee and ankle joints, and larger peak forces were calculated for the Achilles tendon in DJ than in CMJ.

Key words: Countermovement jump — Drop jump — Biomechanics — Electromyography

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Introduction

Vertical jumping ability is of considerable importance in numerous athletic events. Coaches and physical educators have applied various training methods to improve this ability. During the last few years, performing plyometric exercises in general (Wilt 1978) and drop jumps (Komi and Bosco 1978), also called depth jumps (Wilt 1978), in particular, has become very popular in training. Increases in vertical jumping performance after drop jump programmes have been reported in several studies (Blattner and Noble 1979; Steben and Steben 1981; Viitasalo et al. 1981; Bosco and Pittera 1982; Clutch et al. 1983).

Until now, characteristics of the performance of drop jumps have only been described in terms of ground reaction forces (e.g. Asmussen and Bonde-Petersen 1974; Bosco and Komi 1980) and knee angles (e.g. Bosco and Komi 1979; Bosco et al. 1982). The aim of the present study was to provide an extensive biomechanical analysis of drop jumps, and to describe differences between the performance of drop jumps and the performance of countermovement jumps. In order to compare the levels of muscle excitation during drop and countermovement jumps, electromyograms were recorded from several leg mucles.

Subjects and methods

Thirteen male handball players (age 24±3 years; height 1.82±0.05 m; weight 76±8 kg), who were familiar with the performance of drop jumps, participated in this study. Informed consent was obtained from all of them. The subjects followed their usual warm-up routine and subsequently performed several countermovement jumps (CMJ), being vertical jumps with a preparatory countermovement from the erect position on the ground, and several drop jumps (DJ), being vertical jumps preceded by a drop sideways from a height of 40 cm. They were instructed to keep their hands on their hips and to jump as high as possible. No other instructions were given.

During jumping the subjects were filmed with a high-speed camera (16 mm film, 100 frames/s). Simultaneously, vertical and horizontal components of the ground reaction force, as well as point of application, were registered by means of a force-plate (Kistler, type 9281 B) and sampled (sample frequency 500 Hz; resolution 2.5 N). For each frame the positions of landmarks on the 5th metatarsal joint, heel, lateral malleolus, knee joint, greater trochanter and neck (at the level of C5) were determined (see Fig. 1a) with a motion-analyser (Dynamic Frame). After the positions of the landmarks had been filtered (Butterworth 4th-order low-pass filter, cut-off frequency 16 Hz), angles between four body segments (foot, lower leg, upper leg and upper body) were determined (see Fig. 1b). Using data from Dempster (1955) the positions of the mass centres of the body segments and of the whole body were calculated. Angular velocities and angular accelerations as well as linear velocities and accelerations were obtained by differentiation.

After synchronization of force plate and cine data, resultant joint reaction forces, moments, power output and work done were calculated for hip, knee and ankle joints using a four-segment model (Miller and Nelson 1973). Because the resultant moment about the ankles is the sum of the moments exerted by the plantar flexors and those exerted by the dorsiflexors, the moments exerted by the plantar flexors will be equal to, or larger than, the resultant moment about the ankles. The main plantar flexors, m. soleus and m. gastrocnemius, transmit their force to the calcaneus via the Achilles tendon. Assuming that the resultant moment about each of the ankles is solely caused by the force transmitted via the Achilles tendon, this force is given by the quotient of the resultant moment about one ankle and the shortest distance between the Achilles tendon and the axis of rotation at the ankle (Elftman 1939). As an estimate of this latter distance the shortest distance between the Achilles tendon and the tip of the lateral malleolus was used.

According to standard procedures (Basmajian 1974), bipolar surface electrodes (Beckman, lead-off area 0.5 cm^2; electrode distance centre to centre 3 cm) were applied to the skin over five muscle bellies of the left lower extremity (m. rectus femoris, m. vastus medialis, m. soleus, caput laterale and caput mediale of m. gastrocnemius). The positions of the electrodes have been described by Gregoire et al. (1984). EMG signals

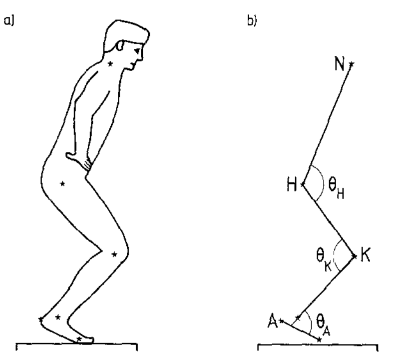

Fig. 1a. Position of markers applied to the skin of the subjects. **b** Definition of angles at joints. *N, H, K* and *A*: neck, hip, knee and ankle respectively; θ_H, θ_K and θ_A: angles at hip, knee and ankle joints respectively

were amplified (DISA type 15 C 01, operating at a band-width between 10 and 500 Hz), full-wave rectified, and low-pass filtered (−3 dB-point at 7.2 Hz, slope 16 dB · $octave^{-1}$). The resulting signal, which will henceforth be referred to as FWRLPF-EMG, was recorded on paper using an ink-jet writer. The mean value of this signal during the push-off phase was determined with the help of a planimeter (Ott).

The duration of the push-off phase was defined as the time between the instant that the mass centre of the body reached its lowest position and the instant of take-off. Jumping height was calculated by subtracting from the highest position attained by the mass centre of the body the height of this mass centre when standing upright. Because peak values of moments and power output about joints were reached at or after the start of the push-off phase, attention is focussed on this phase in the presentation and discussion of results.

Mean curves of time histories of variables during the push-off phase were calculated after synchronization of individual curves at the instant of take-off. For CMJ, mean curves were calculated for the whole group of subjects. As will be elucidated when presenting the results, the variance of results obtained for the drop jump could be reduced by splitting the group into two subgroups, which will be referred to as "counter group" ($n=6$) and "bounce group" ($n=7$). In the counter group, height was 1.82±0.03 m, and weight was 75±9 kg. In the bounce group, height was 1.82±0.06 m, and weight was 76±9 kg. For DJ, mean curves were calculated for these two groups separately.

Hypotheses concerning differences between jumps were tested for significance using a Student *t*-test for paired comparisons (two-tailed $P<0.05$). Differences mentioned in results and discussion are statistically significant.

Results

Time histories of vertical ground reaction force during CMJ and DJ of two subjects are shown in Fig. 2a and b. The curves for CMJ are very similar, but the curves for DJ are strikingly different. As can be seen, the subject represented in Fig. 2a is already in the push-off phase, while the subject represented in Fig. 2b has not even landed on the ground. It will be clear that a large variance is found if both subjects are included when calculating a mean curve for DJ. Individual values for the duration of the push-off phase and the duration of downward movement in DJ are shown in Table 1. The whole group could be divided into a subgroup, in which the duration of the push-off phase was less than 200 ms ($n=7$) and a subgroup in which the duration of this phase was more than 260 ms ($n=6$). There was no difference between the two subgroups in performance of CMJ. The mean curve for CMJ of the whole group, and mean curves for DJ of the two subgroups, are shown in Fig. 2c. As can be seen, there was little difference between the time histories of vertical ground reaction force in CMJ and DJ for the group in which the push-off phase lasted more than 260 ms. Therefore, this subgroup will hence-

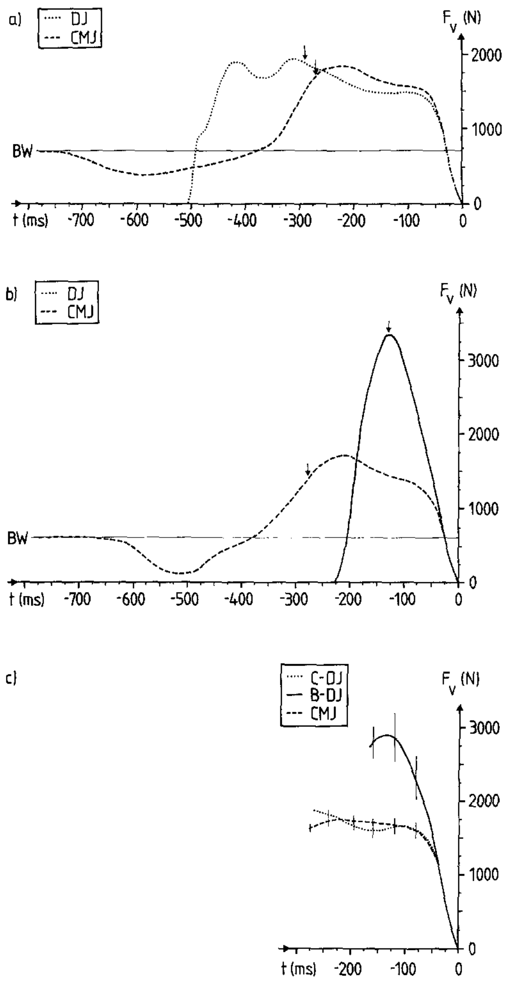

Fig. 2a, b. Time histories of vertical ground reaction force (F_V) during countermovement jumps (*CMJ*) and drop jumps (*DJ*) of two subjects. *BW*, body weight; *arrows* indicate start of push-off phase. **c** Mean curves (±SEM) of F_V for CMJ of the whole group ($n = 13$) and for DJ of the counter group (*C− DJ*, $n = 6$) and bounce group (*B− DJ*, $n = 7$), plotted from the average start of the push-off phase. Time is expressed relative to the instant of toe-off ($t = 0$)

Table 1. Combinations of duration of push-off phase ($t_{push\text{-}off}$) and duration of downward movement ($t_{downward}$) in drop jumps by 13 subjects

$t_{push\text{-}off}$ (s):	0.13 0.13 0.16 0.17 0.19 0.19 0.20 0.26 0.26 0.26 0.27 0.28 0.32
$t_{downward}$ (s):	0.10 0.12 0.12 0.14 0.17 0.19 0.16 0.17 0.20 0.32 0.24 0.23 0.22

forth be referred to as the "counter group". The other subgroup will be referred to as the "bounce group", because of the general appearance (a movement of small amplitude) of the DJ. Since the variance of other variables in DJ was also smaller within each subgroup than in the whole group, the results will be presented for the two groups separately.

The results for a number of variables concerning jumping performance are shown in Table 2 (counter group) and in Table 3 (bounce group). In the counter group, no differences were found in these variables between CMJ and DJ. In the bounce group, however, the mass centre of the body was lowered less; the duration of the push-off phase was shorter; the vertical ground reaction force at the start of the push-off phase was greater; the average vertical ground reaction force during the push-off phase was greater (see also Fig. 2c); and total work done and total energy gain during the push-off phase were smaller in DJ than in CMJ. Ratios of total work done to total energy gain during the push-off phase did not differ from 1.0 ($P > 0.05$). No difference was found in jumping height between CMJ and DJ.

Figure 3 presents the mean curves of joint variables (angle, angular velocity, moment and power output) for CMJ of the whole group and for DJ of both subgroups. Values for joint varia-

Table 2. Characteristics of jumps by the counter group ($n = 6$). Mean values (±SD) are given for countermovement jump (CMJ), for drop jump (DJ), and for difference between jumps (DJ − CMJ)

	CMJ	DJ	DH − CMJ
$h_{mcb,min}$ (m)	−0.35 ± 0.07	−0.33 ± 0.09	0.02 ± 0.06
$h_{mcb,max}$ (m)	0.49 ± 0.06	0.47 + 0.07	−0.02 ± 0.03
$t_{push\text{-}off}$ (s)	0.28 ± 0.02	0.28 ± 0.02	0.00 ± 0.03
$F_{V,start}$ (N)	1792 ± 215	1941 ± 295	149 ± 228
$F_{V,mean}$ (N)	1555 ± 182	1562 ± 182	7 ± 125
W_{tot} (J)	597 ± 116	559 ± 144	−38 ± 66
ΔE_{tot} (J)	613 ± 104	580 ± 131	−33 ± 81

$h_{mcb,min}$: minimal height reached by the mass centre of the body relative to the height of this mass centre when standing upright; $h_{mcb,max}$: maximal height reached by the mass centre of the body relative to the height of this mass centre when standing upright (jumping height); $t_{push\text{-}off}$: duration of push-off phase; $F_{V,start}$: vertical ground reaction force at start of push-off phase; $F_{V,mean}$: mean value of vertical ground reaction force during push-off phase; W_{tot}: total work done during push-off phase; ΔE_{tot}: total energy gain during push-off phase

Table 3. Characteristics of jumps by the bounce group ($n=7$). Mean values ($\pm$SD) are given for countermovement jump (CMJ), for drop jump (DJ), and for difference between jumps (DJ−CMJ). See Table 2 for abbreviations

	CMJ	DJ	DJ−CMJ
$h_{mcb,min}$ (m)	−0.33 ± 0.05	−0.21 ± 0.05	0.12 ± 0.04*
$h_{mcb,max}$ (m)	0.42 ± 0.04	0.42 ± 0.05	0.00 ± 0.02
$t_{push\text{-}off}$ (s)	0.28 ± 0.04	0.17 ± 0.03	−0.11 ± 0.04*
$F_{V,start}$ (N)	1613 ± 228	3052 ± 834	1439 ± 706*
$F_{V,mean}$ (N)	1531 ± 182	2082 ± 368	551 ± 332*
W_{tot} (J)	510 ± 54	432 ± 70	−78 ± 45*
ΔE_{tot} (J)	511 ± 72	440 ± 64	−71 ± 49*

* Difference between jumps statistically significant ($P<0.05$)

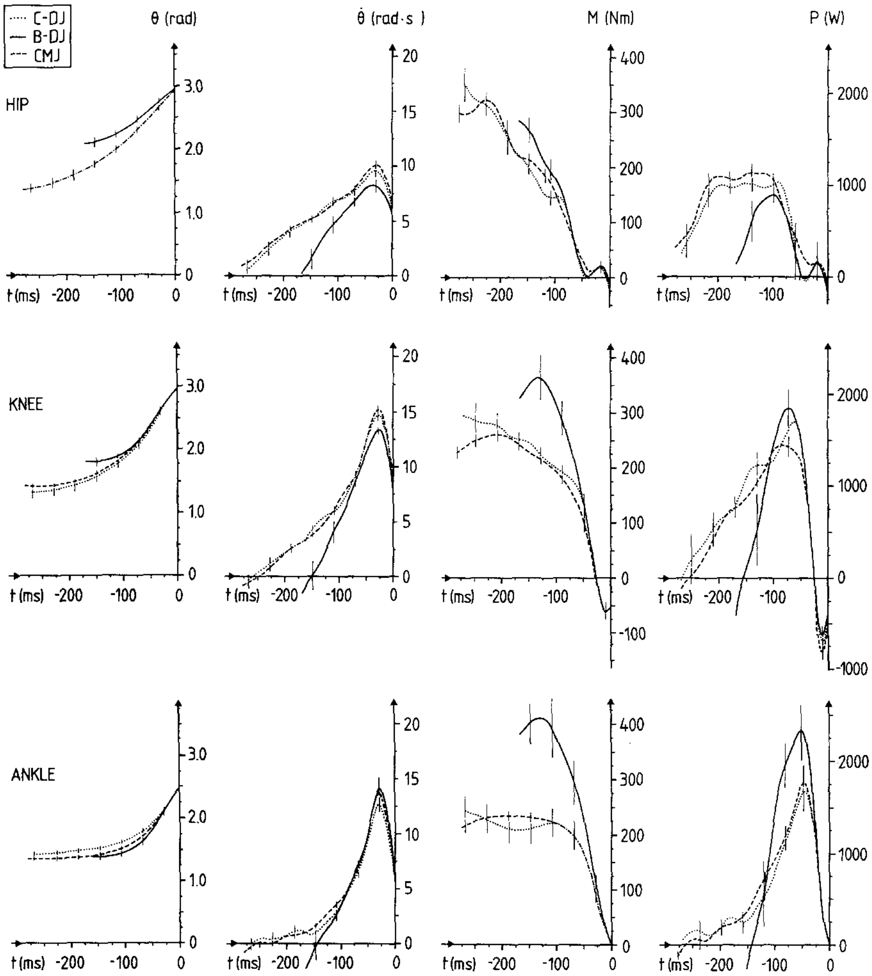

Fig. 3. Mean curves ($\pm$SEM) of angles (θ), angular velocities ($\dot{\theta}$), resultant moments (M) and resultant power output (P) at the hip, knee and ankle joints for the countermovement jump (CMJ) of the whole group ($n=13$) and for drop jumps of the counter group ($C-DJ$, $n=6$) and bounce group ($B-DJ$, $n=7$). Time is expressed relative to the instant of toe-off ($t=0$). Curves are plotted from the average start of the push-off phase

bles calculated from individual curves are shown in Table 4 (counter group) and in Table 5 (bounce group). In the counter group, the minimal angle at the ankles was somewhat larger, greater resultant vertical joint reaction forces occurred at the knees and ankles, and the amount of work done at the hips as well as its contribution to the total amount of work done were smaller in DJ than in CMJ. In the bounce group, the differences between CMJ and DJ were much more pronounced. The fact that in this group the mass centre of the body was lowered less in DJ than in CMJ (Table 3) appears to be due to greater minimal angles at the hips and knees. In DJ of the bounce group, larger values for moments and average power output are found at the knee and ankle joints, and larger resultant vertical joint reaction forces occurred than in CMJ. Moreover, the amount of work done and

Table 4. Joint variables in jumps by the counter group ($n = 6$). Mean values ($\pm$SD) are given for countermovement jump (CMJ), for drop jump (DJ), and for difference between jumps (DJ − CMJ)

			CMJ	DJ	DJ − CMJ
θ_{min}	(rad)	Hips	1.21 ± 0.30	1.38 ± 0.31	0.17 ± 0.22
		Knees	1.34 ± 0.14	1.32 ± 0.30	− 0.02 ± 0.24
		Ankles	1.34 ± 0.10	1.39 ± 0.12	0.05 ± 0.04*
M_{start}	(Nm)	Hips	343 ± 109	351 ± 78	8 ± 53
		Knees	247 ± 35	308 ± 132	61 ± 110
		Ankles	236 ± 59	249 ± 70	13 ± 51
M_{max}	(Nm)	Hips	366 ± 98	368 ± 62	2 ± 48
		Knees	279 ± 43	331 ± 125	52 ± 98
		Ankles	266 ± 46	279 ± 46	13 ± 34
M_{mean}	(Nm)	Hips	185 ± 27	177 ± 33	− 8 ± 36
		Knees	189 ± 27	206 ± 54	17 ± 41
		Ankles	204 ± 31	195 ± 51	− 9 ± 31
P_{max}	(W)	Hips	1551 ± 317	1338 ± 350	−213 ± 339
		Knees	1657 ± 376	1762 ± 585	105 ± 344
		Ankles	1886 ± 512	1776 ± 578	−110 ± 309
P_{mean}	(W)	Hips	805 ± 198	673 ± 159	−132 ± 128
		Knees	667 ± 132	764 ± 304	97 ± 195
		Ankles	595 ± 122	578 ± 195	− 17 ± 130
W	(J)	Hips	234 ± 67	187 ± 57	− 47 ± 44*
		Knees	193 ± 44	215 ± 105	22 ± 65
		Ankles	171 ± 33	157 ± 48	− 14 ± 31
% W		Hips	39 ± 5	33 ± 4	− 6 ± 5*
		Knees	32 ± 2	37 ± 10	5 ± 9
		Ankles	29 ± 5	29 ± 10	0 ± 6
$F_{V,max}$	(N)	Hips	1546 ± 237	1814 ± 244	268 ± 310
		Knees	1781 ± 244	2307 ± 325	526 ± 404*
		Ankles	1859 ± 258	2553 ± 379	694 ± 478*

θ_{min}: minimal angle; M_{start}: moment at start of push-off phase; M_{max}: maximal moment; M_{mean}: mean moment during push-off phase; P_{max}: maximal power output; P_{mean}: mean power output during push-off phase; W: work done; % W: relative contribution to total work done; $F_{V,max}$: maximal resultant vertical joint reaction force.
* Difference between jumps statistically significant ($P < 0.05$)

its contribution to the total amount of work done were greater for the ankles and smaller for the hips in DJ than in CMJ.

Values calculated for the peak force transmitted by the Achilles tendon ranged from 1.5 to 2.7 times body weight in CMJ, and from 3.2 to 7.0 times body weight in DJ of the bounce group.

In Fig. 4 the average FWRLPF-EMGs during the push-off phase in DJs of the two subgroups are expressed as percentages of the average FWRLPF-EMG during CMJ. In the counter group no differences were found between DJ and CMJ. In the bounce group, however, the mean FWRLPF-EMGs of both heads of m. gastrocnemius were larger in DJ than in CMJ.

Discussion

Hubley and Wells (1983) adopted the work-energy approach to determine individual joint contributions to vertical jumping performance. For countermovement jumps they found values for total work done during the push-off phase of 8.5 $J \cdot kg^{-1}$, and calculated relative contributions of the hip, knee and ankle joints of 28%, 49% and 23% respectively. In the present study, the total work done during the push-off phase in CMJ was on the average 7.3 $J \cdot kg^{-1}$, and the relative contributions of the hip, knee and ankle joints were 38%, 32% and 30% respectively. The ratio of total work done to total energy gain during the push-off phase did not differ from 1.0 either in this study or in the study of Hubley and Wells (1983), which indicates that the methods used lead to valid results. Therefore, the differences between values found in this study and values reported by Hubley and Wells (1983) are probably due to inter-individual differences.

With regard to the performance of drop jumps, it was found in this study that some subjects (those allotted to the counter group) made a large downward movement (i.e. they bent their hips and knees considerably before starting to

Table 5. Joint variables in jumps by the bounce group ($n = 7$). Mean values ($\pm$SD) are given for countermovement jump (CMJ), for drop jump (DJ), and for difference between jumps (DJ – CMJ). See Table 4 for abbreviations

			CMJ	DJ	DJ – CMJ
θ_{min}	(rad)	Hips	1.44 ± 0.17	2.06 ± 0.23	0.62 ± 0.22*
		Knees	1.48 ± 0.08	1.76 ± 0.20	0.28 ± 0.18*
		Ankles	1.30 ± 0.07	1.32 ± 0.08	0.02 ± 0.07
M_{start}	(Nm)	Hips	269 ± 56	270 ± 73	1 ± 110
		Knees	229 ± 87	407 ± 87	178 ± 73*
		Ankles	193 ± 38	420 ± 134	227 ± 112*
M_{max}	(Nm)	Hips	344 ± 67	305 ± 82	– 39 ± 100
		Knees	276 ± 51	414 ± 79	138 ± 67*
		Ankles	246 ± 42	440 ± 122	194 ± 96*
M_{mean}	(Nm)	Hips	179 ± 39	128 ± 52	– 51 ± 46*
		Knees	180 ± 37	211 ± 40	31 ± 25*
		Ankles	193 ± 28	272 ± 64	79 ± 42*
P_{max}	(W)	Hips	1405 ± 289	1203 ± 366	– 202 ± 509
		Knees	1481 ± 403	1936 ± 483	455 ± 286*
		Ankles	1829 ± 358	2425 ± 868	596 ± 702
P_{mean}	(W)	Hips	687 ± 196	485 ± 236	– 202 ± 260
		Knees	593 ± 175	875 ± 167	282 ± 87*
		Ankles	581 ± 134	1322 ± 627	741 ± 508*
W	(J)	Hips	189 ± 52	84 ± 47	– 105 ± 57*
		Knees	163 ± 47	146 ± 36	– 17 ± 32
		Ankles	158 ± 27	203 ± 50	45 ± 26*
% W		Hips	37 ± 9	19 ± 10	– 18 ± 11*
		Knees	32 ± 10	34 ± 9	2 ± 7
		Ankles	31 ± 4	48 ± 12	17 ± 8*
$F_{V,max}$	(N)	Hips	1586 ± 170	2785 ± 663	1199 ± 609*
		Knees	1779 ± 199	3393 ± 856	1614 ± 757*
		Ankles	1847 ± 220	3640 ± 973	1793 ± 860*

* Difference between jumps statistically significant ($P < 0.05$)

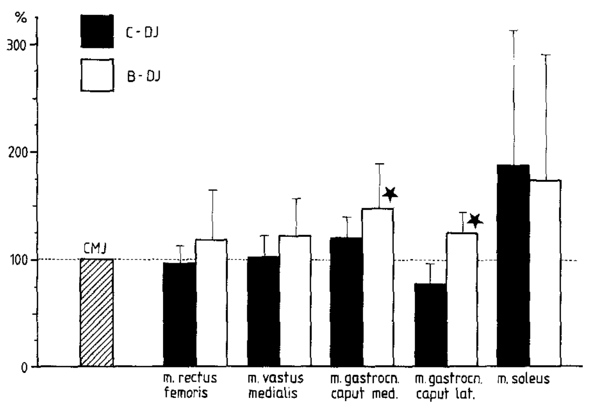

Fig. 4. Mean FWRLPF-EMG of five muscle bellies for drop jumps of the counter group (*C – DJ*, $n = 6$) and bounce group (*B – DJ*, $n = 7$), expressed as a percentage of the mean FWRLPF-EMG during the push-off phase of the countermovement jump (CMJ). * Difference between jumps statistically significant ($P < 0.05$)

push off), whereas other subjects (those allotted to the bounce group) made only a small downward movement and remained for a relatively short time on the ground. The choice by a subject of one jumping style or the other could not be related to anthropometrical variables, and seemed to be arbitrary. In fact, results of pilot work suggest that, after having been demonstrated, both jumping styles can be employed by every subject.

The results obtained for the push-off phase in DJ appeared to depend on jumping style. In the counter group, the push-off phase of DJ closely resembled that of CMJ, whereas in the bounce group the push-off phases of DJ and CMJ differed in several respects. In the latter group, the minimal angles in hip and knee joints were greater in DJ than in CMJ. As a consequence, the joints were extended over a smaller range during the push-off phase, and the push-off phase was of shorter duration in DJ. In the hip joints this was accompanied by a smaller amount of work done. In the knee joints, however, the amount of work done was the same in DJ and CMJ because average moment and power output were larger in DJ. A larger average moment and power output in DJ were also found at the ankle joints, where they resulted in more work done. These changes in amount of work done lead to a smaller relative contribution of the hip joints, and a larger contribution of the ankle joints to the total amount of work done during the push-off phase in DJ. The larger knee extending and plantar flexing moments found in DJ at the start of the push-off phase and during the push-off phase may be related to the influences of the rapid pre-stretch of knee extensors and plantar flexors, which occurs immediately after touch-down. This pre-stretch may potentiate the contractile parts of the muscles (Cavagna et al. 1968; Cavagna and Citterio 1974). Moreover, it may increase the level of muscle excitation by evoking a functional stretch reflex (Melvill Jones and Watt 1971) or a monosynaptic reflex (Dietz et al. 1979; Schmidtbleicher et al. 1979), the mechanical effect of the latter being probably small (Gottlieb and Agarwal 1979). In this regard the higher FWRLPF-EMGs of both heads of m. gastrocnemius in DJ are noteworthy. A decrease in the influence of rapid pre-stretch with time may explain why in the counter group, in which the push-off started later after touch-down than in the bounce group, no difference was found between moments in DJ and moments in CMJ.

It is not unlikely that the enhancement of moments and mean power output about knees and ankles above values occurring in CMJ, which was found in DJ of the bounce group, induces training effects in the long run. However, the enhancement of mean power output was accompanied by a large increase in the peak values of the resultant reaction forces at the joints (Table 5) and the force exerted on the Achilles tendon, despite the fact that the platform from which the subjects dropped was only 40 cm above the ground. The latter force reached values of up to 7.0 times body weight, which approximates the value of 9.0 times body weight reported by Wilhelm (1974) for the ultimate tensile strength of the Achilles tendon in dynamic circumstances. In the literature, training programmes are described in which subjects drop from heights of 1.10 m (Clutch et al. 1983) or more than 3 m (Dursenev and Raevsky 1979). Before repeated drops from such heights can be recommended, further research into the influences of height of drop and jumping style on the values attained by joint variables is required.

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