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SCIENTIFIC PAPER

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Running head: Effects of Arms and Countermovement on Vertical Jumping

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The Effects of Arms and Countermovement on Vertical Jumping

ABSTRACT

Countermovement (C) and arm-swing (A) characterize most jumping. For determination of their effects and interaction, 18 males jumped for maximal height from a force platform four ways: C, A ; C, no A ; no C, A ; no C, no A. For all jumps, vertical velocity peaked 0.03 sec before, and dropped 6-7% by takeoff. Peak positive power averaged over 3,000 W, and occurred about 0.07 s before takeoff, shortly after maximum vertical ground reaction force (VGRF) and just before peak vertical velocity. Both C and A significantly ($p < 0.05$) improved jump height, but A's effect was greater, enhancing both height of the total body center of mass (TBCM) at takeoff and post-takeoff TBCM rise. C only affected the latter. Use of A resulted in less unweighting and slower descent of the TBCM during C, higher TBCM position at the bottom of C, higher peak VGRF, higher peak positive power, and lower negative power. C increased pre-takeoff jump duration by 71-76%, increased average positive power, and resulted in large positive and negative impulses. Correlation of peak power with post-takeoff jump height was 0.88. Body weight and post-takeoff jump height effectively predicted peak power ($r = 0.94$). The results lend insight into which jumping techniques are most appropriate for given sports situations.

HUMAN POWER OUTPUT, FORCE PLATFORM, SPORT TECHNIQUES, STRETCH-SHORTEN CYCLE, IMPULSE, NEGATIVE POWER

INTRODUCTION

Vertical jumping is an integral part of the high jump track-and-field event and sports such as volleyball, diving and basketball. Some form of jumping is involved in most sports. Running can be viewed as a series of alternating left and right leg jumps. Even olympic weightlifting has been described by coaches as a jumping-type movement. It is understandable why the vertical jump-and-reach test has become a commonly used measure of athletic ability.

Most jumping is preceded by a countermovement, which can be described as a quick bend of the knees during which the body's center of mass drops somewhat before being accelerated upwards. Enoka (3) reported a 12 percent jump height advantage with the countermovement among a group of 44 subjects. The countermovement utilizes the stretch-shortening cycle in which eccentric muscle stretching stores elastic energy which is in part released during immediately subsequent concentric muscle contraction. There is some evidence that individuals with predominantly fast twitch muscle fibers are better able to recover stored elastic energy in high speed countermovement jumps with short knee angular displacement, while individuals with predominantly slow twitch fibers can recover more stored elastic energy in slower jumps involving greater knee angular range (2). The ability to recover stored elastic energy may also be affected by previous training (4).

It has been theorized that improvement in performance with the countermovement may in part result from potentiation, during the eccentric stretching phase, of myoelectric activity during the subsequent concentric contraction phase. However, contribution of such a mechanism appears unlikely because integrated EMG's have been shown to be no greater during vertical jumps with a countermovement than without one (1).

An additional theory proposed to explain the performance-enhancing effects of the countermovement is that a concentric contraction immediately following an eccentric stretch begins with the muscle already under considerable tension, making more chemical energy available for generation of force (3). The existence of such a mechanism has not been directly tested by experimentation.

Even though it leads to higher jumping, countermovement cannot always be effected before a vertical jump. In some sports situations, an athlete is already in a squatting or semi-squatting position before jumping. Also, when jumping in response to the movement of another athlete or a ball, a player may not have time to perform a countermovement.

Vertical jumps are often characterized by swinging of the arms. Luhtanen and Komi (5) measured the impulse produced during no-countermovement jumps using only one body part at a time, and found a 10% contribution from the arms to take-off velocity. Payne (6) reported that the use of arms superimposed one extra late peak onto the GRF curve produced by the leg and body action and ensured that the center of gravity was as high as possible before flight began (about 12% higher with arms than without). The author also stated that the arms produced "extra force for the propulsion of the body" resulting in a 5% (7.6 cm) greater jump height. Also noted was a lower starting position for the jump without arms.

It is not always possible to use the arms to assist in vertical jumping. A player might be precluded from swinging the arms because they are occupied in throwing or manipulating a ball or other implement. The arms might have to be held in a raised position to prepare for blocking or catching a ball.

In none of the previous studies have the use of arms and countermovement been examined together. Because both are recognized as important factors in

jumping, it would seem important to know how they interact with each other. The present study was undertaken to accomplish this goal. In addition, it was intended that close examination of more jump variables than in previous studies, including those describing the timing of various sub-events of a jump, would provide information that would aid in selection of the most advantageous jumping techniques for given sports situations.

METHODOLOGY

The experiment was conducted in accordance with the policy statement of the American College of Sports Medicine (MEDICINE AND SCIENCE IN SPORTS 10:ix-x, 1978) and U.S. Army regulation AR 70-25 on use of volunteers in research, which require that human subjects give free and informed voluntary consent before participation.

Eighteen physically active male subjects (Table 1) jumped maximally from a force platform four different ways in random order: arms with countermovement (AC), arms with no countermovement (ANC), no arms with countermovement (NAC), and no arms with no countermovement (NANC). Each subject performed three trials of each type jump for a total of 12 jumps. Subjects rested between jumps until they felt no residual fatigue, usually from one to three minutes. The starting position for all countermovement jumps was an upright posture with the arms down at the sides (Figure 1). For the AC jumps the subject swung his arms back while letting his body drop and his knees bend, then jumped up as high as possible while swinging the arms in a downward, forward, upward arc. For the NAC jumps, the subject held his arms down at his sides while letting his body drop and his knees bend, then jumped up as high as possible while keeping his arms at his sides. For the ANC jump, the subject first

assumed the knees-bent, arms-back position and upon command from the experimenter jumped vertically as high as possible while swinging the arms in a downward, forward, upward arc. For the NANC jumps, the subject assumed the knees-bent, arms-down position and upon command from the experimenter jumped vertically as high as possible while keeping his arms at his sides.

All jumps were performed on a model LG6-1-1 0.6 meter by 1.2 meter force platform connected to a model SGA6-3 amplifier system, both from AMTI (Newton MA). The output signal representing vertical ground reaction force (VGRF) was fed into a Hewlett-Packard (Lexington MA) 310 microcomputer via an Infotek (Anaheim CA) model AD200 12-bit analog-to-digital converter board sampling at 500 times per second. A computer program calculated values for 40 variables describing the jump. Data files from all the individual jumps were transferred to a VAX 780 mainframe computer (Digital Equipment Corp., Maynard MA) where they were amalgamated and processed statistically using BMDP (Los Angeles CA) software.

Force platform information was used to generate curves of vertical position and velocity of the total body center of mass (TBCM) during each jump. The calculations were based on the principle that impulse equals change in momentum, or force multiplied by time equals change in the product of mass and velocity. Thus, for a jumper, change in TBCM vertical velocity during each sampling interval equals net external vertical force acting on the body multiplied by the time period over which the force is applied divided by body mass. The net force was taken as the VGRF reading from the force platform minus body weight. The change in velocity, and the updated absolute velocity was calculated for each 500th-of-a-second time interval. The velocity curves were integrated to get a curve of vertical position of the TBCM. Instantaneous power was calculated as VGRF times the concurrent velocity of the TBCM.

Maximum vertical displacement attained by the TBCM after take-off was calculated from TBCM vertical velocity as the feet left the force platform using standard formulas for projectile motion (3).

RESULTS

Vertical travel of the TBCM during a jump can be broken down into two segments. The first is the rise of the TBCM from its location in the pre-jump position to its location just as the feet leave the ground. The second is the rise of the TBCM after takeoff. Thus technique can be seen to improve jumping in two ways: 1) by increasing height of the TBCM at takeoff, and 2) by increasing pre-takeoff net vertical ground reaction impulse (VGRI) which enhances takeoff velocity and in turn, post takeoff TBCM rise.

Peak pre-takeoff TBCM rise is not comparable between the countermovement and no-countermovement jumps, because the former jumps began in a standing position, while the latter jumps began in a lower, knees-bent position. Use of the arms increased TBCM height at takeoff (Table 2) because of its effects on body mass distribution. However, while the countermovement resulted in significantly ($p < 0.05$) greater pre-takeoff vertical TBCM travel relative to its lower starting position, it did not increase TBCM height relative to the standing position because it did not affect body geometry at takeoff.

For each jump, the sum of the pre- and post-takeoff TBCM rises equalled peak positive TBCM displacement, or total jump height. Use of the arms resulted in a TBCM position at takeoff 4.8 cm and 4.2 cm higher than without the arms for the countermovement and no-countermovement conditions respectively. Because the TBCM travelled farther from starting position to takeoff in a no-countermovement jump, the advantage to pre-takeoff TBCM rise

attributable to the arms amounted to 10% for the no-countermovement jump and 40% for the countermovement jump.

Both the use of arms and countermovement had significant positive effects on jump height after takeoff. Use of the arms had the greater effect, enhancing net VGRI by 10%, yielding increased takeoff velocity and a 6 cm or 21% higher rise of the TBCM after takeoff. The countermovement increased net VGRI by only about 3%, and post takeoff jump height by 2 cm or 6%. The difference in percentage increase between VGRI and post-takeoff TBCM rise is because the latter is related to the square of takeoff velocity, while VGRI is directly proportional to takeoff velocity ($(1.1)^2=1.21$ and $(1.03)^2=1.06$).

While arm-swing enhancement of the total jump resulted from both raising TBCM height at takeoff and increasing net pre-takeoff VGRI, improvement by the countermovement was due only due to the latter. The arm-swing resulted in a 9-10 cm advantage for the total jump, which translates to 14% and 27% for the no-countermovement and countermovement conditions respectively. It should be noted that the latter percentage is more relevant to most sport situations, where the height one can jump above a standing, not a semi-squatting position is usually most important.

Figure 2 shows that, as the countermovement jumps were initiated, ground reaction force dropped below body weight. The degree of unweighting was greater when the arms weren't used, under which condition the VGRF dropped to a mean 36% of body weight during the countermovement. When the arms were used, VGRF only dropped to a mean of 47% of body weight. For the countermovement jumps, the TBCM moved downward at a significantly faster peak speed when the arms weren't used. Apparently, the upward/backward swing of the arms partially offset the downward acceleration of the rest of the non-arm body mass.

In the countermovement jumps, the arm-swing resulted in a mean 3 cm less extensive drop in the TBCM. Estimates from measurement of photographs indicate that about half that was due to the upward/backward position of the arms at the bottom of the jump and the rest to slightly less knee flexion.

Slight countermovement, which was not visually observable, was picked up through computer analysis of the no countermovement jumps. Minimum VGRF was slightly below body weight during these jumps, indicating a small degree of unweighting. It appears that, even with practice, most subjects could not completely eliminate preparatory countermovement. It was observed that even slight movements of the head and trunk could account for the small amounts of unweighting, even when the knees showed no countermovement at all. Some of the unweighting during the ANC jumps can be explained by the initial downward acceleration of the arms from their up and back starting position.

The graphs portraying the countermovement condition show the TBCM back at its starting position after the jumps. With no countermovement, the TBCM ended up higher than where it started because the jumpers began with bent knees and stood fairly erect after completing the jumps.

Peak VGRF was significantly greater when the arms were used than when they weren't. Countermovement didn't show a significant effect on peak VGRF, but there was a greater effect of arms during jumps without (+8%) than with (+2%) countermovement which showed up as statistical interaction. During the NAC jumps, peak VGRF occurred when the TBCM was at its low point, probably because the type of jump was associated with relatively high downward TBCM velocity during the countermovement, requiring high forces to slow TBCM descent. For the other jumps, peak VGRF occurred closer to takeoff.

Peak positive vertical velocity paralleled the differences in jump height among conditions. It should be noted that peak velocity was not at takeoff,

but consistently 0.03 sec before takeoff (Table 3). It appears that during the last 30 or so milliseconds before takeoff the large muscles around the hip and thigh had already contracted fully, leaving only the plantar flexors in position to continue to generate VGRF. However, based on the force-velocity relationship (7) and the speed at which they were contracting, these muscles probably could not exert force equivalent to body weight, and the TBCM actually decelerated, so that takeoff velocity was only about 93% of peak velocity.

Vertical velocity at takeoff is a direct function of pre-takeoff net VGRI, or area under the VGRF-time curve, and body mass. Thus it is not surprising that arms and countermovement affected net VGRI just as they did takeoff velocity and jump height. The countermovement was associated with large positive VGRI, but also with sizable negative VGRI that cancelled out a good portion of the positive one, so that the countermovement had a relatively small but significant effect on net VGRI.

Peak positive power averaged well over 3,000 W overall, and close to 4,000 W for the AC condition. Only the use of the arms had significant enhancing effect on peak positive power. In contrast, only the countermovement had significant enhancing effect on average positive power. By definition, the muscles generated negative power when TBCM vertical velocity and VGRF were opposite in sign, as when the body's rate of descent was slowed by VGRF during the latter part of the countermovement. During the countermovement jumps, both peak and average negative power were significantly greater when the arms weren't used. This is consistent with the relatively high unweighting and downward TBCM velocity for the no-arm jumps. Times of occurrence of power peaks were relatively consistent across jumps, with the negative and positive peaks respectively occurring about 440 and 70 milliseconds before takeoff.

Because positive power is the product of TBCM vertical velocity and VGRF, it is not surprising that peak positive power generally occurred between peak vertical velocity and peak VGRF.

The time of first movement listed in Table 3 indicates when the jumps began. It can be seen that the countermovement jumps took 71-76% longer from initial movement to takeoff than did the jumps without countermovement.

Correlations were performed to identify variables most closely associated with jump height. Pre-takeoff TBCM rise, being mainly a function of subject height, didn't correlate well with any of the variables describing important aspects of jump technique. Taller subjects could get their TBCMs higher in absolute terms before their feet left the ground, irrespective of force, impulse and power patterns manifested. There were correlations, in the 0.3 to 0.5 range, of pre-takeoff TBCM rise with both positive and net VGRI, but they probably reflect the tendency for taller subjects to be heavier and somewhat stronger. Table 4 shows correlation of technique variables with both post-takeoff TBCM rise and total jump height. Total jump height was not comparable between the countermovement and no-countermovement conditions, because the lower starting body position of the former jumps resulted in greater difference between starting and highest TBCM positions. However, post-takeoff TBCM rise was comparable for all jumps. Correlation coefficients were similar in many cases for post-takeoff TBCM rise and total jump height, but were generally better for the former.

The correlations show that average power, in contrast to peak power, is not reflected well by jump height. This is probably because average power is greatly affected by total time taken to execute the jump movement. The time can be lengthened or shortened by slowing down or speeding up parts of the movement preceding the important high power phase that occurs within the last 150 milliseconds of the jump.

The reason that peak negative VGRF rate of change was well correlated with jump height was probably because higher jumpers left the ground faster, and as their feet lost contact, VGRF changed quickly from a high value to zero. The fair correlations between jump height and time of peak power can be explained by higher jumps being faster, with all jump stages temporally closer to takeoff. The fact that correlation of net VGRI with post-takeoff TBCM rise was only good and not excellent reflects the fact that the TBCM rise is dependent not only upon net VGRI but on body mass as well. Positive VGRI didn't relate as well to jump height as did net VGRI, because positive VGRI can be offset at least in part by negative VGRI. Peak VGRF didn't correlate very well with jump height because power is more relevant than force to jump height, and power generation requires concurrence of high force and high velocity. For similar reasons peak rate of VGRF development also was not closely associated with jump height.

The very good correlations of peak positive power with peak post-takeoff TBCM rise suggest that the latter variable would be a good predictor of peak power. This is particularly true for the AC condition, which represents the more natural type of jump. Because force is a component of power, an attempt was made to predict peak power from body weight in addition to post-takeoff jump height using multiple linear regression. It was found that for all the jump-types together the following equation produces peak power (P) estimates in watts from post-takeoff jump height (H) in cm and body weight (W) in newtons which correlate 0.94 with observed peak power:

$$P = 77.2H + 3.72W - 1598$$

For the AC or "natural" jumps the following equation predicts peak positive power with a correlation coefficient of 0.96:

$$P = 73.9H + 3.29W - 1122$$

It would be convenient to be able to estimate peak power from total jump height since the latter is more easily measured than post-takeoff TBCM rise. For the no-countermovement jumps, regression equations using body weight and total jump height could only produce correlation coefficients in the range of 0.7. However, for the countermovement jumps, peak power could be predicted from total jump height (H) and body weight (W) with a correlation coefficient of 0.96 using the following equation:

$$P = 65.3H + 3.08W - 1759$$

Discussion

The arms contributed a mean 10% to takeoff velocity in the present experiment for both the countermovement and no-countermovement conditions, a proportion very similar to the effect reported by Luhtanen and Komi (5) in an experiment in which no-countermovement jumps were performed using either the whole body or individual body parts alone. Jump heights in the present study were similar to those reported by Enoka (3), but his subjects showed a 4 cm countermovement effect compared with the 2 cm one reported here.

Readers must be cautioned that the total jump height used in the equation developed to predict peak power represents the maximum vertical travel of the TBCM. This is not necessarily the same as the height obtained from the widely

used jump-and-reach test. The jump-and-reach test starts with the subject in a flatfooted stance with one arm raised touching a wall. The subject then jumps as high as possible touching the wall again, and jump height is the vertical distance between touch locations. Inserting the jump-and-reach score into the regression equations might not lead to accurate estimation of peak power.

In order to estimate how closely mean jump-and-reach scores matched total TBCM rise, the same group of subjects were reassembled a few weeks after the initial testing to perform the jump-and-reach test. The mean jump-and-reach score was 46.9 ± 8.5 cm compared with 52.2 ± 9.4 for the total TBCM rise. The fact that jump-and-reach scores were less than TBCM rise distances is probably because the force plate jumps started with the arms down, providing a lower TBCM starting position, and because the requirement of touching a wall is more restrictive than jumping straight up into the air. Even though they were performed more than a month apart, the two jump measures showed a correlation coefficient of 0.92. The high correlation suggests that a regression-derived equation would estimate with good accuracy peak power from jump-and-reach scores and body weight. The best way to produce information to develop such an equation would be to have subjects perform jump-and-reach tests from a force platform so that peak power production could be directly measured.

One might question how the arm-swing increases VGRI. The obvious answer is that upward acceleration of the arms must be accompanied by concomitant force at the feet. However, observations of the jumpers shows that in most cases the arms decelerate relative to the rest of the body as they approach the fully raised position before takeoff, thus reducing VGRI. The fact that the arms return to zero vertical velocity relative to the rest of the body means their net effect on VGRI should be about zero. How then does the arm-swing increase net VGRI? The answer appears to be in the force-velocity relationship of

muscle contraction (7). When the muscles crossing the hip and thigh are in the most advantageous position to exert VGRF, the upward swing of the arms create a downward force at the shoulders on the rest of the body. This slows down the contraction of the large quadriceps and gluteal muscles allowing them to contract at a slower velocity where they can exert more force. Pre-takeoff VGRI thus increases. When the arms decelerate near the end of their swing, they pull up on the rest of the body. However, this occurs when the knees and hips are almost fully extended, and the muscles around them aren't in position to generate much VGRF anyway.

It would be incorrect to conclude that since the use of arms and countermovement positively affect jump height they should both always be employed in sports involving jumping. In sports like high-jumping and long-jumping, where an athlete wants to get every last millimeter out of a jump, the use of both arms and countermovement is clearly called for. On the other hand, countermovement jumps take considerably longer to perform, and result in only modest performance gain. Thus, there are many sports situations in which it is preferable to jump without a countermovement. Often, in basketball, volleyball, or other team sport in which jumping plays a major part, it is well worth sacrificing 2 cm in jump height in order make a defensive move more quickly. In a rebounding situation in basketball, an athlete might position himself with bent knees, trying to anticipate the direction in which the ball will bounce off the rim or backboard, then leap in the right direction at the appropriate time. If the athlete does not need the highest two centimeters of his jumping potential in order to reach the ball, then the no-countermovement jump provides a clear advantage in movement time.

There are sports situations in which an athlete is precluded from using the arm swing for jumping because the hands are occupied by an implement or

ball. Even when the hands are free the best alternative is not always to use the arm swing. For example, when an athlete must reach up on very short notice to grab a basketball rebound or to block a volleyball spike, the hands can reach the ball most quickly if they start in the up position, and on queue, go directly to the ball without going down for the swing. That is true, of course, only if the athlete can jump high enough to reach the ball without the arm swing. Thus there are trade-offs with the arm swing just as there are for the countermovement.

The quantitative information on jumping technique provided in this paper can assist coaches and athletes in determining the kinds of jump most effective for given sports situations. The peak power estimation equations can lead to the development of effective and easy to use maximal power output tests.

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TEXT TO FIGURES

Figure 1. Sequences for the four types of jump:

arms/countermovement = A,B,C arms/no countermovement = B,C

no arms/countermovement = A,D,E no arms/no countermovement = D,E

Figure 2. The lower graph for each of the four jumping conditions shows VGRF (solid), and TBCM vertical velocity (dashed). The upper graphs depict power output of the VGRF (solid) and TBCM position (dashed). Vertical lines: a = start of TBCM upward movement; b = loss of foot contact with ground; c = resumption of foot contact with ground.

Table 1. Subject characteristics (mean $\pm$ SD)

height (m)	1.79 $\pm$ 5.4
body mass (kg)	74.7 $\pm$ 7.7
age (yrs)	28.5 $\pm$ 6.9

Table 2. VGRF, VGRI, power production, and TBCM position and velocity (mean $\pm$ SD) during the four types of jump. Displacements are relative to the starting position, which was lower for the countermovement jumps. Pre-takeoff negative VGRI occurred as the feet were leaving the force platform.

Event	significant effects		NC	A	C	
	A	C			NA	A
Peak pre-takeoff TBCM rise (cm)	*	*	43.3 $\pm$ 7.0	47.7 $\pm$ 7.3	12.2 $\pm$ 1.6	16.9 $\pm$ 1.8
Peak post-takeoff TBCM rise(cm)	*	*	27.4 $\pm$ 6.6	33.2 $\pm$ 7.9	29.1 $\pm$ 7.4	35.3 $\pm$ 8.4
Peak + TBCM displacement (cm)	*	*	71 $\pm$ 11	81 $\pm$ 12	41 $\pm$ 8	52 $\pm$ 9
Peak - TBCM displacement (cm)	*	*	-1.2 $\pm$ 0.9	-1.4 $\pm$ 0.9	-35 $\pm$ 6.7	-32 $\pm$ 6.2
Maximum VGRF (N)	*		1562 $\pm$ 219	1687 $\pm$ 205	1697 $\pm$ 308	1725 $\pm$ 218
Minimum VGRF (N)	*	*	717 $\pm$ 63	700 $\pm$ 84	263 $\pm$ 125	342 $\pm$ 126
Peak + velocity (m/s)	*	*	2.47 $\pm$.26	2.70 $\pm$.28	2.54 $\pm$.28	2.77 $\pm$.29
Peak - pre-takeoff vel. (m/s)	*	*	-.02 $\pm$.02	-.03 $\pm$.04	-1.21 $\pm$.27	-1.07 $\pm$.28
Peak + VGRF rate of change(N/s)			1957 $\pm$ 868	1708 $\pm$ 630	2145 $\pm$ 1193	2090 $\pm$ 899
Peak - VGRF rate of change(N/s)	*		-7896 $\pm$ 1907	-8421 $\pm$ 1998	-7644 $\pm$ 1691	-8514 $\pm$ 1830
Peak + power (W)	*		3262 $\pm$ 626	3804 $\pm$ 684	3216 $\pm$ 607	3896 $\pm$ 681
Peak - power (W)	*	*	-13 $\pm$ 17	-22 $\pm$ 27	-1208 $\pm$ 469	-1050 $\pm$ 437
Takeoff velocity (m/s)	*	*	2.30 $\pm$.28	2.53 $\pm$.30	2.37 $\pm$.31	2.61 $\pm$.32
+ VGRI (Ns)	*	*	186 $\pm$ 25	205 $\pm$ 28	281 $\pm$ 47	289 $\pm$ 48
- countermovement VGRI (Ns)	*	*	-1.3 $\pm$ 1	-2.6 $\pm$ 3	-91.2 $\pm$ 25	-81.7 $\pm$ 25
- pre-takeoff VGRI (Ns)	*		-13.1 $\pm$ 2.9	-12.4 $\pm$ 2.8	-13.0 $\pm$ 3.0	-12.1 $\pm$ 2.8
Net VGRI (Ns)	*	*	172 $\pm$ 25	190 $\pm$ 28	177 $\pm$ 27	195 $\pm$ 28
Average + power (W)		*	1260 $\pm$ 371	1337 $\pm$ 339	1450 $\pm$ 436	1470 $\pm$ 351
Average - power (W)	*	*	-9 $\pm$ 9	-12 $\pm$ 11	-417 $\pm$ 101	-374 $\pm$ 102
Avg. rate of force devel. (N/s)	*		2643 $\pm$ 1429	2791 $\pm$ 1158	4121 $\pm$ 2302	3021 $\pm$ 1858

A = arms NA = no arms C = countermovement NC = no countermovement
 positive (+) = upwards negative (-) = downwards
 VGRF = vertical ground reaction force
 VGRI = vertical ground reaction impulse
 TBCM = total body center of mass
 * = p<.05

Table 3. Time (sec) of event relative to takeoff (negative = pre takeoff).

Event	significant effects		Time of event (s)			
	A	C	NC		C	
	A	C	NA	A	NA	A
maximum VGRF	*	*	-.13+.06	-.11+.02	-.26+.08	-.15+.10
minimum VGRF	*		-.50+.10	-.50+.10	-.66+.11	-.70+.12
Peak + VGRF rate of change	*		-.30+.06	-.28+.10	-.44+.11	-.41+.15
Peak - VGRF rate of change			-.02+.006	-.02+.006	-.02+.006	-.02+.007
Peak + TBCM vert. displacement	*	*	.24+.03	.26+.03	.24+.03	.27+.03
Peak + power			-.07+.01	-.07+.01	-.07+.01	-.07+.01
Peak - power			-.44+.10	-.44+.09	-.43+.08	-.45+.08
Landing	*	*	.48+.06	.53+.07	.50+.07	.55+.07
First movement	*		-.48+.13	-.49+.09	-.82+.12	-.86+.12
First + VGRF	*		-.47+.11	-.46+.10	-.50+.08	-.52+.08
Peak - pre takeoff TBCM vel.	*		-.44+.10	-.46+.09	-.50+.08	-.52+.08
Peak + TBCM velocity	*		-.03+.006	-.03+.006	-.03+.006	-.03+.006

A = arms NA = no arms C = countermovement NC = no countermovement
 positive (+) = upwards negative (-) = downwards
 VGRF = vertical ground reaction force
 VGRI = vertical ground reaction impulse
 TBCM = total body center of mass
 * = $p < .05$

Table 4. Correlations of selected variables with jump height.

Variable		Correlation coefficient (r)				
		All Jumps	No Counter movement		Counter movement	
			No Arms	Arms	No Arms	Arms
Peak positive power	I	0.88	0.84	0.86	0.86	0.91
	II	0.05	0.56	0.66	0.89	0.91
Time of peak positive power	I	0.68	0.82	0.69	0.78	0.66
	II	0.31	0.67	0.59	0.74	0.61
Average positive power	I	0.54	0.57	0.56	0.59	0.49
	II	0.07	0.36	0.38	0.54	0.44
Maximum VGRF	I	0.49	0.35	0.49	0.53	0.49
	II	0.05	-0.06	0.18	0.56	0.49
Positive VGRI	I	0.51	0.76	0.78	0.61	0.60
	II	-0.35	0.66	0.75	0.64	0.61
Net VGRI	I	0.83	0.82	0.80	0.82	0.79
	II	0.42	0.71	0.77	0.84	0.80
Peak positive VGRF rate of change	I	0.34	0.44	0.57	0.37	0.31
	II	0.00	0.04	0.41	0.40	0.29
Peak negative VGRF rate of change	I	-0.81	-0.82	-0.83	-0.83	-0.84
	II	-0.44	-0.53	-0.67	-0.81	-0.82

positive = upwards

I = peak post-takeoff TBCM rise

negative = downwards

II = total peak TBCM rise

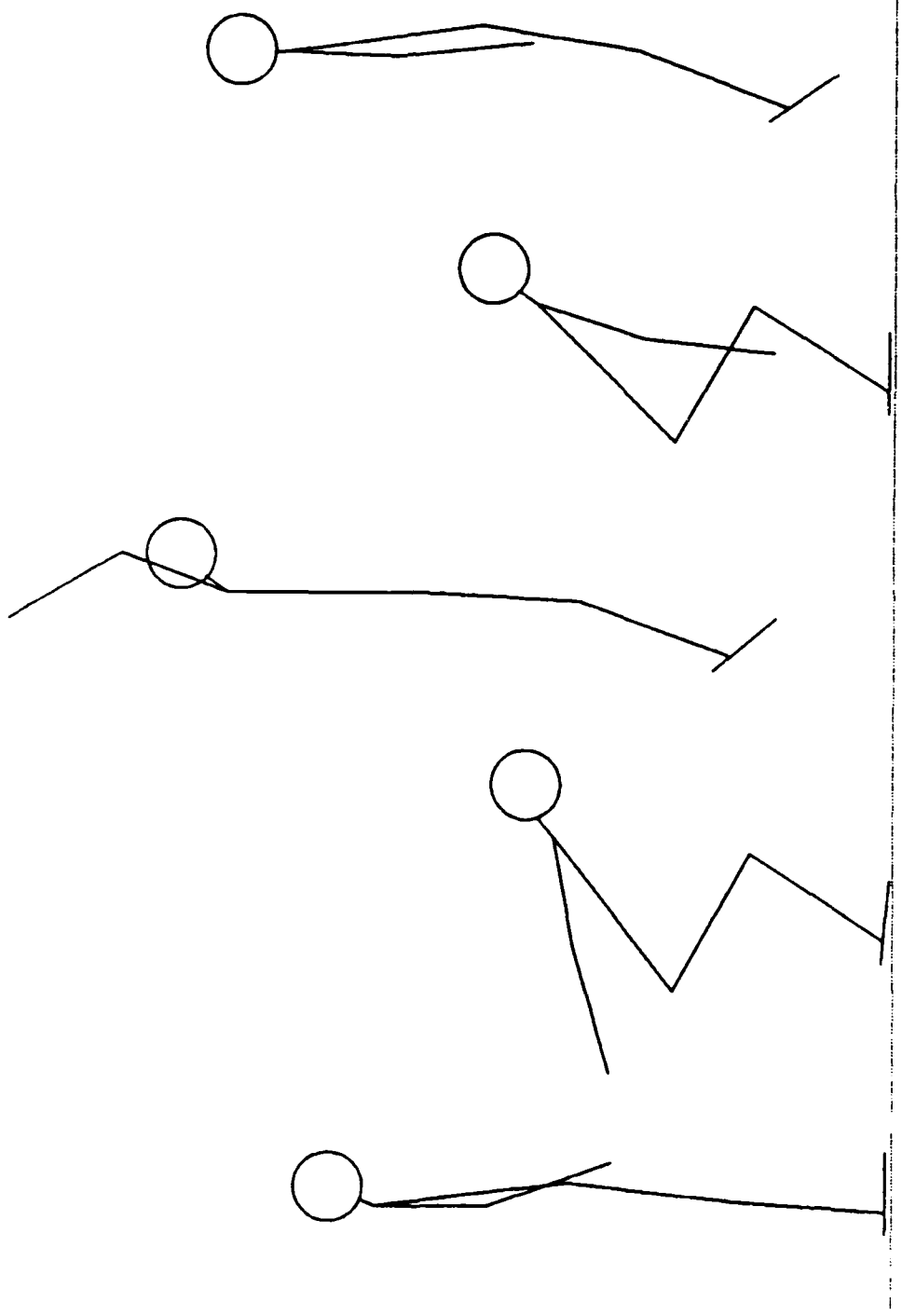
VGRF = vertical ground reaction force

VGRI = vertical ground reaction impulse

TBCM = total body center of mass

NOTE ON U.S. ARMY HUMAN RESEARCH

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision.



A

B

C

D

E

< FIG 1 >

NANC

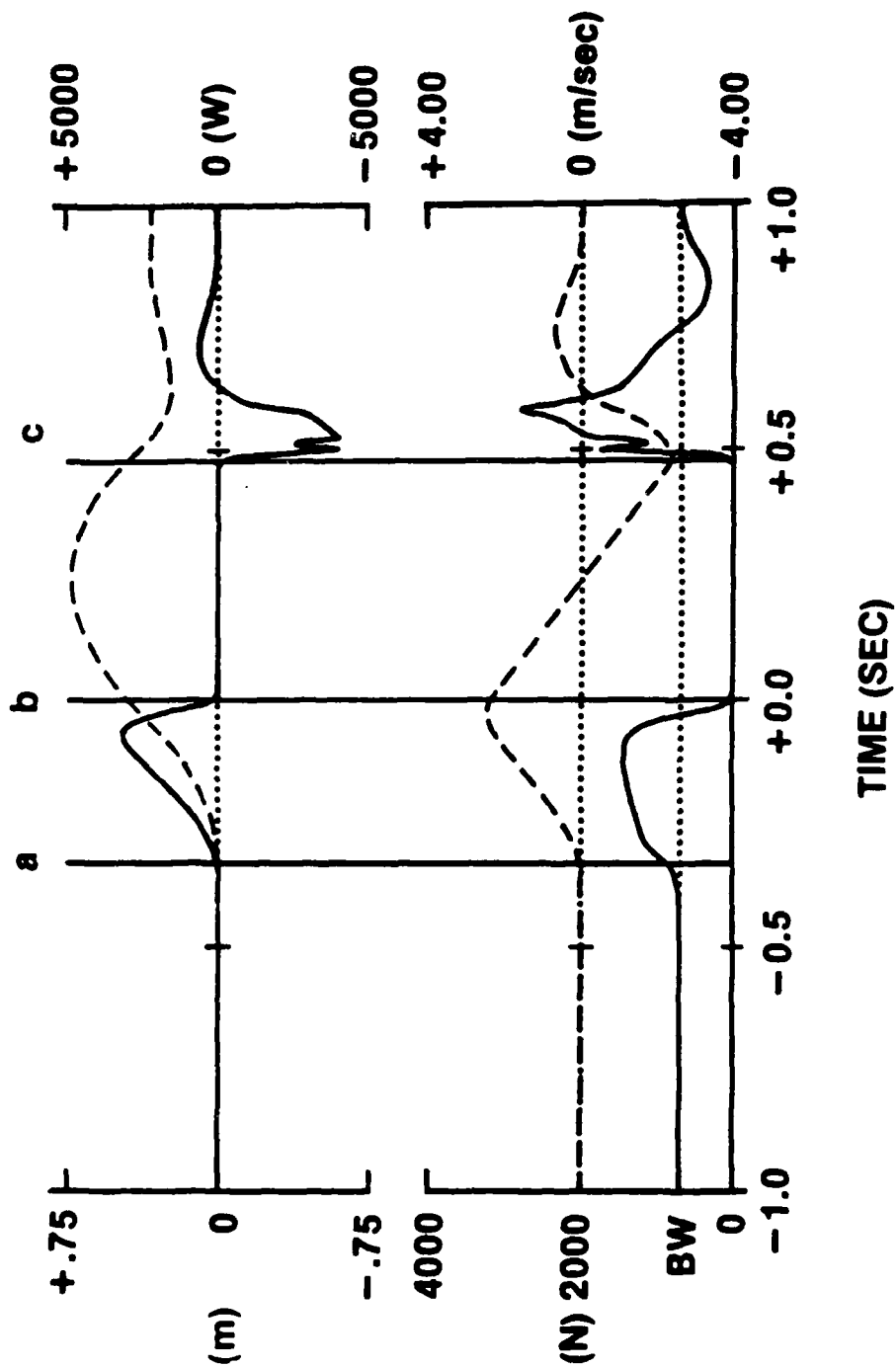


FIG 2

upper left

NAC

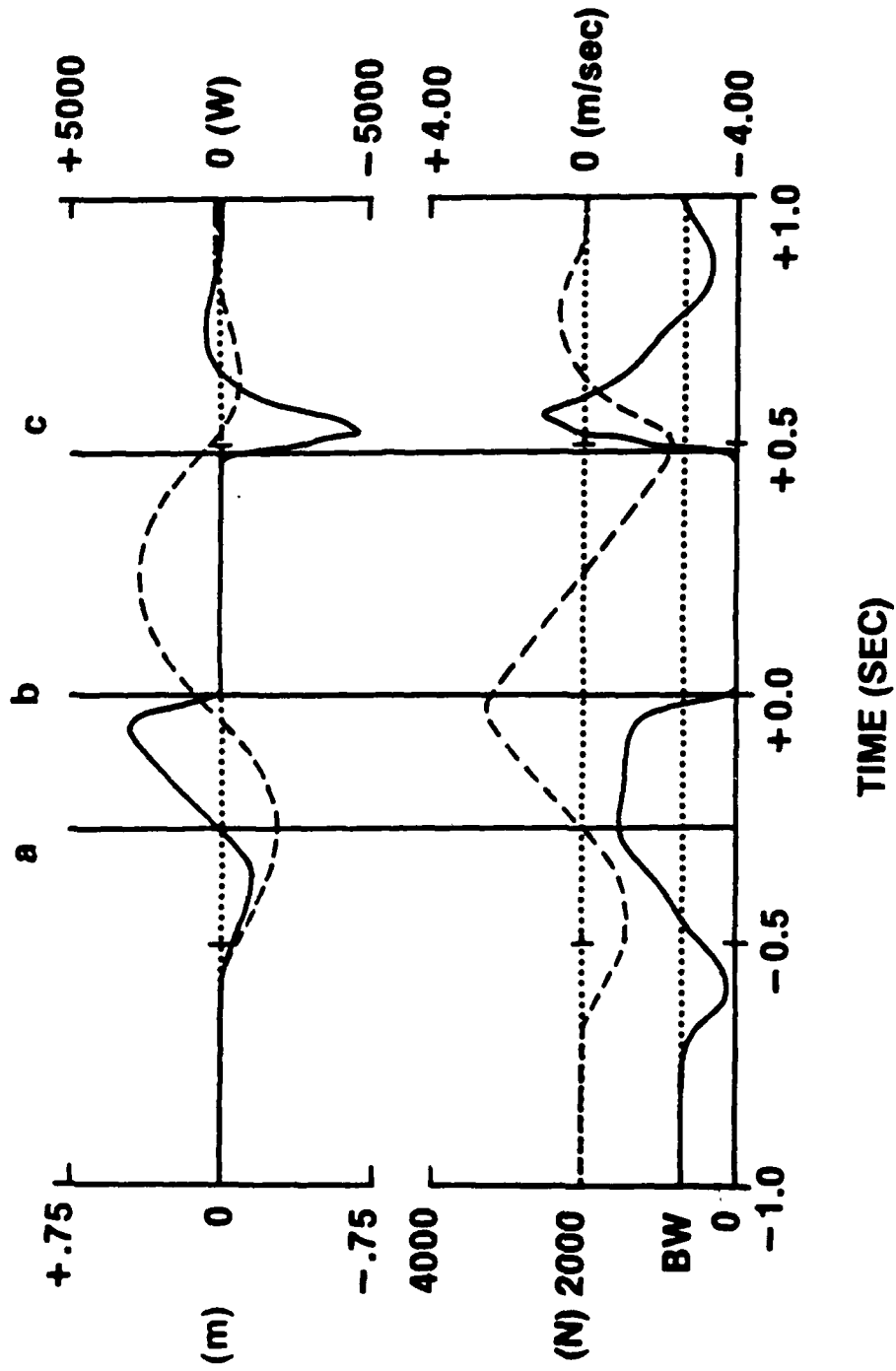
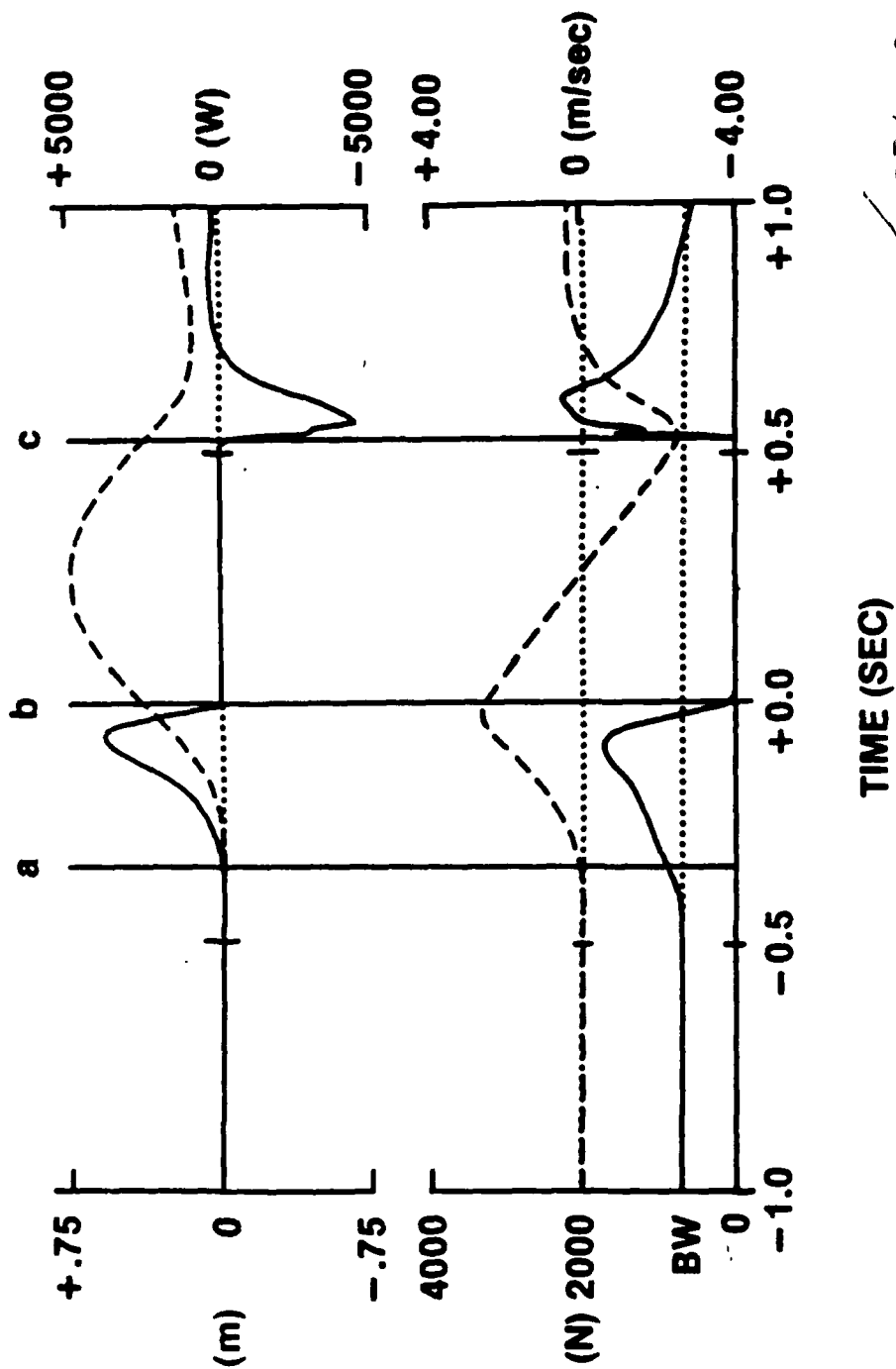


FIG 2
upper right

ANC



TIME (SEC)

FIG 2
Lower left

AC

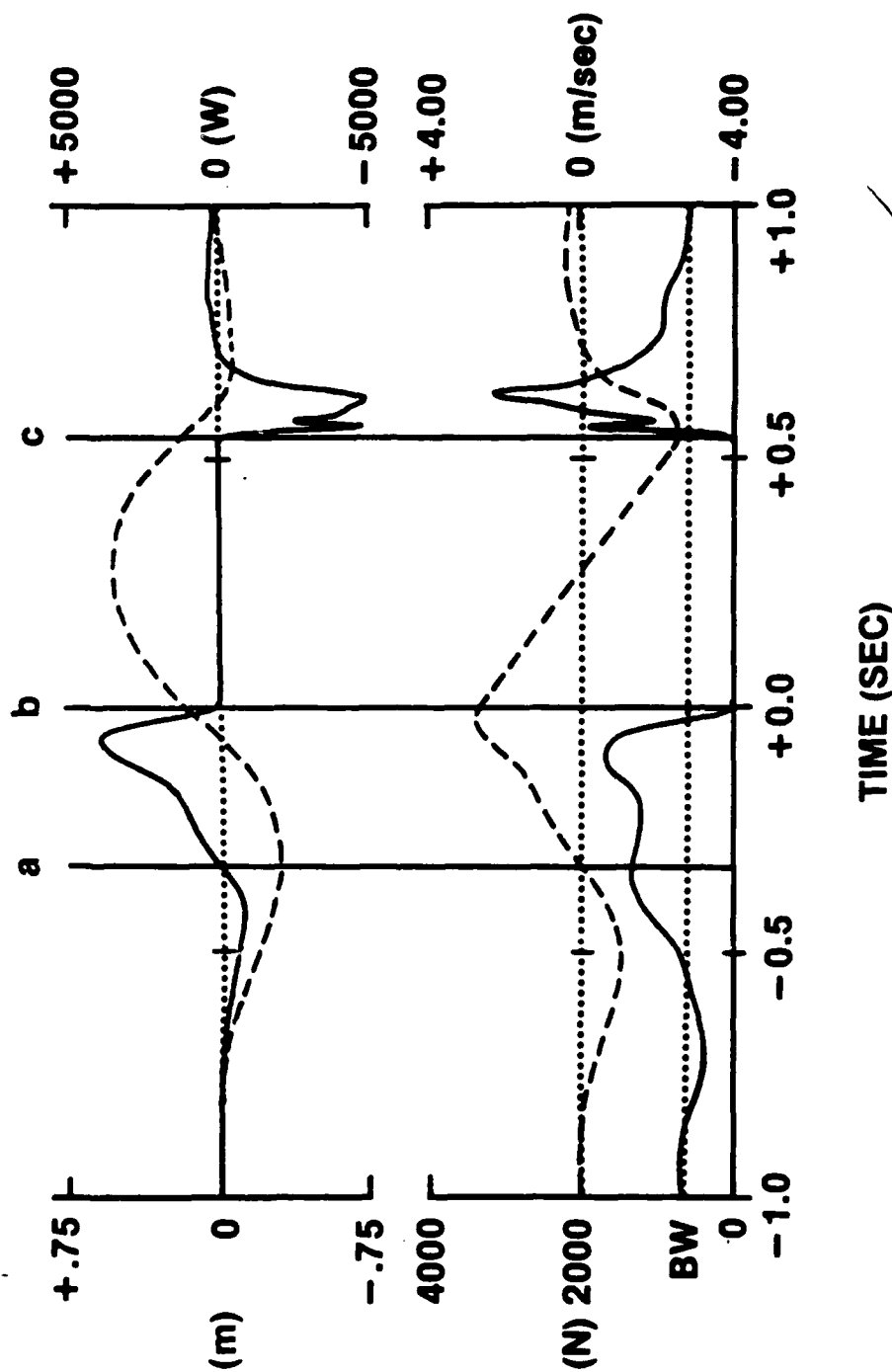


Fig 2

Lower right