WORK CHARACTERISTICS OF STANDING BROAD AND VERTICAL JUMPING

by

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ABSTRACT

The purpose of this study was to determine the contributions made by the leg muscle groups to the work done in standing broad and vertical jumping. A secondary purpose was to examine the principles of summation and continuity of joint forces as they apply to these jumps.

Twelve subjects were filmed while jumping from a force platform. They performed a minimum of three maximal standing broad and vertical jumps, with countermovements and use of the arms permitted. The jumps were filmed at a rate of 50 frames per second while, synchronously, ground reaction force data were collected at 50 Hz. Link segment analysis and inverse dynamics methods were used to compute the net muscle moments of force and the power and work outputs created by these moments of force.

The jumps were examined over two time periods, during both the propulsive phase of jumping and the entire jump. The work-energy approach was used to determine the relative contributions of the muscles crossing the ankle, knee and hip joints to the total work done at the leg joints. A work-energy analysis (i.e. the ratio of net mechanical work done at 6 joints to the gain in total mechanical energy) for the two types of jumps during the two time intervals of interest produced values all less than 1.0. This suggests that there were other sources of work that subjects were using and which were not measured in the analysis. As well,

this suggests that the link segment model utilized may not have been appropriate for all subjects.

For the standing broad jump the contributions of the ankle, knee and hip muscles during the propulsive phase were 30.2, 18.6 and 51.2 percent, respectively, while their contributions over the entire jump were 31.5, 17.0 and 51.5 percent, respectively. The respective contributions of the ankle, knee and hip joints for the vertical jump during the propulsive phase were 33.0, 24.8 and 42.2 percent and over the entire jump the contributions were 39.2 (ankle), 22.4 (knee) and 38.4 (hip) percent.

Two-tailed correlated t-tests were done to check for differences in relative contributions of both the ankle and knee joints to the work done at the leg joints in standing broad and vertical jumping. The only significant difference ($p<.01$) occurred at the ankle joint over the entire jump. Relatively, the muscles crossing the ankle joint did significantly more work in vertical jumping than in standing broad jumping.

One-way ANOVAs with repeated measures were utilized to test the differences between relative joint contributions for each type of jump during the two time periods examined. Neuman-Keuls post hoc method was used to evaluate the multiple pairwise comparisons. There were two main findings. First, over the entire jump, the muscles crossing the hip joint did significantly more work than those of the knee joint during both standing broad ($p<.01$) and vertical jumping ($p<.05$). Then for the propulsive phase, there was significantly more work generated at the hip joint than at either the knee joint or the ankle joint during both vertical jumping (knee: $p<.01$; ankle: $p<.05$) and standing broad jumping (knee: $p<.01$; ankle: $p<.01$).

Results for the evaluation of the summation and continuity principles supported the principle of summation of joint forces as the muscles of all three leg joints, for all subjects, were net generators of positive work during the propulsive phase of standing broad and vertical jumping. The continuity of joint forces principle, however, was not fully supported as the sequencing of muscular contractions was not always from proximal to distal as expected.

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INTRODUCTION

While there has been a large amount of research devoted to the standing jumps, most of the studies have been kinematic analyses. Unfortunately, kinematic analyses only describe movement; they do not provide information about the forces which cause movement. The kinetic investigations which have been undertaken to study jumping have concentrated almost exclusively on the vertical jump. Despite this fact the movement pattern itself is still not well understood because research has mainly focused upon using vertical jumping as a tool for examining total body work, energy or power instead of determining where and how work and power are being generated or absorbed. Only a joint power analysis allows the work done by the muscles crossing a joint to be calculated which enables the role and importance of the muscles involved to be ascertained.

Elftman (1939a, 1939b), while looking at walking, was the first to combine joint reaction forces and net joint moments with segmental and joint kinematics to calculate the rate of change of energy for the leg segments, the rate of energy transfer through the leg joints due to joint forces and the rate of work done by muscles crossing the joints. He later extended this work to running (Elftman, 1940). Since that time, joint power analysis has been used to examine the contribution of the leg joints to walking (Bresler and Berry, 1951; Cappozzo _et al_., 1976; Morrison, 1970; Zarrugh, 1981), race walking (White and Winter, 1985), jogging (Winter, 1983), running (Robertson, 1985), jumping (Hubley and Wells, 1983; Robertson and Fleming, 1986) and soccer kicking (Robertson and Mosher, 1985).

Hubley and Wells (1983) used the work-energy approach to quantify the amount of positive work contributed by the muscles crossing the hip, knee and ankle joints during the propulsive phase of vertical jumping. They found similar relative work contributions by the leg joints for both countermovement and squat jumps.

Robertson and Fleming (1986) looked at the propulsive phase of both standing vertical and standing broad jumping. They showed that there was a difference between relative leg joint contributions for the two types of jumps. However, the strength of their finding was lessened by the small number of subjects involved, particularly in the vertical jump.

Two biomechancal principles which are thought to apply to jumping are the principle of summation of joint forces or moments and the principle of continuity of joint forces or moments. Simply stated, the principle of summation of joint forces says that to produce the fastest, most powerful movement possible, all the joints that can contribute to the movement must be used and used to their fullest extent. This principle has been described by Broer and Zernicke (1979), Dyson (1962), Jensen and Schultz (1977), Luttgens and Wells (1982), Morehouse and Cooper (1950), Norman

(1975), Northrip et al. (1974), Simonian (1981) and the Level I Coaching Theory Manual of the National Coaching Certification Program (1979a). The sequencing of muscular contractions for a movement is explained by the principle of continuity of joint forces which says that the order of muscle contractions should be from the proximal to the distal muscle groups (Broer and Zernicke, 1979; Dyson, 1962; Gowitzke and Milner, 1980; Luttgens and Wells, 1982; National Coaching Certification Program, 1979a; Norman, 1975; Plagenhoef, 1971). This implies that the muscle groups contract from the largest to the smallest, from the strongest to the weakest or from from the slowest to the fastest.

The usefulness of a biomechanical principle depends upon the ease with which the principle can be directly applied to physical activity. A problem that arises for the athlete and coach is how to apply the principle to athletic performance when often there is little or no established criteria for evaluating whether or not a principle is being followed. Luttgens and Wells (1982), the National Coaching Certification Program (1979a, 1979b, 1981) and Norman (1975) all state that through observation of a performance it is possible to determine if an athlete is adhering to the principles of summation and continuity of joint forces. Therefore, if a movement is as fast as possible, if all the joints are used through as large a range of motion as possible and if the movement is continuous, then it is thought that both the summation and continuity principles will be in evidence. The problem with this approach is that simple observation does not provide information concerning the forces involved in a movement. This can only be established through a kinetic analysis of the movement.

PURPOSE

The main purpose of this study was to determine the relative contribution of the muscles crossing the hip, knee and ankle joints to the total (resultant) work done at the leg joints during maximal standing vertical jumping and standing broad jumping. A secondary objective was to determine if the principles of summation of joint forces and of continuity of joint forces held true for maximal standing broad and vertical jumping by establishing criteria to make the determination possible. A final aim was to identify any common patterns of joint energy generation or absorption, for the two types of jumps, among a test group of jumpers.

METHODOLOGY

PROCEDURE

Subjects. Twelve students, who were either currently or formerly active in community college or university sports which involved jumping, performed a minimum of three trials of both the standing vertical and the standing broad jump. Since the subjects were encouraged to jump maximally, countermovements and use of the arms were permitted. One of each type of jump for every subject was chosen for analysis. Before jumping, anthropometric data of sex, age, mass, height and segment lengths were collected on each subject. Subject information is presented in Table 1.

Markers. Because both the standing vertical and standing broad jumps were assumed to be bilaterally symmetric motions, one side of the body was used to represent both sides. The subjects had markers placed on the right side of their bodies over appropriate landmarks at the toe, ball (middle of the fifth metatarsal-phalangeal joint), heel, ankle (lateral malleolus of the fibula), knee (lateral femoral epicondyle, about 2 cm superior to the joint line), hip (greater trochanter of the femur), shoulder (on the humerus, about 2 cm inferior to the acromial process of the scapula), elbow (lateral epicondyle of the humerus) and wrist (middle of the inferior radio-ulnar joint). The opening of the outer ear was used as the marker for the head (Dempster, 1955).

Table 1. Sex, age, mass, height and sport of subjects

Subject	Sex	Age (years)	Mass (kg)	Height (cm)	Sport
MB	M	21	84.0	188.0	Basketball
RB	M	25	77.9	185.5	Basketball
REB	M	21	80.6	193.0	Basketball
DE	M	22	64.8	175.3	Basketball
KG	M	21	86.2	182.9	Triple jump
CJ	F	23	65.8	179.1	High jump
PJ	M	21	95.4	190.5	Basketball
KK	M	24	95.3	193.0	Basketball
MM	M	31	65.1	171.5	Basketball
CP	M	19	81.5	188.0	Basketball
LS	M	22	78.0	182.9	Basketball
NS	M	21	80.2	190.5	Basketball
Mean		22.6	79.6	185.0	
S.D.		3.0	10.0	6.6	

DATA COLLECTION AND ANALYSIS

The jumps were performed from a Kistler force platform which had the following characteristics: linearity, $\leq \pm$ 1 % full scale output; hysteresis, $\leq \pm$ 0.5 % full scale output; crosstalk, $\leq \pm$ 3 % in all directions. Ground reaction forces were collected by a Data General microNova computer (MP/200) at a rate of 50 Hz. Simultaneously the jumps were recorded on cinefilm at 50 frames per second by a Locam camera placed orthogonal to the plane of the jumps. The shutter pulse correlator of the camera was conditioned to trigger analog-to-digital (A/D) conversions of the six channels of the force platform. When a button was pressed, a relay was activated that turned on an LED electronic pulse to the A/D converter of the computer which enabled matching of the force plate and camera records. The raw force data and x coordinate of the center of pressure data were low-pass digitally filtered with an upper cutoff frequency of 20 Hz. Faulty force platform data precluded analysis of six standing broad jump trials.

The film was projected an average of 15 percent life-size onto a drafting table. Body marker coordinates were digitized using a Numonics Graphics Calculator interfaced with the Data General minicomputer. The resolution of the digitization system was 0.5 mm while the digitization error was calculated to have a RMS error of less than 3 mm, on average. The raw cinefilm data were transmitted to an Amdahl 470/V8 computer where they were scaled and then refined using a fractional linear transformation based on the work of Woltring (1980) to remove linear distortions caused by camera or projector misalignment. Next the coordinate information was filtered using a low-pass filter with an upper cutoff frequency of 6 Hz to remove high frequency noise and then differentiated using finite difference equations (Pezzack et al., 1977).

A seven component link segment model was used to represent subjects for analysis purposes. The seven segments were the foot, lower leg, thigh, trunk, head-neck, upper arm and forearm-hand. This approach has been validated by Pezzack and Norman (1981). Anthropometric constants used for all subjects were obtained from Winter (1979) and derived from Dempster's (1955) cadaver studies. Using link segment modelling, incorporating anthropometric, kinematic and force plate data, the vertical and horizontal forces and net moments of force at the ankle, knee, hip, elbow, shoulder and neck joints were calculated by inverse dynamics (Winter, 1979) using the computerized software package BIOMECH (Kinesiology Department, University of Waterloo).

Joint Power. The instantaneous power developed at each joint by the net moment of force was computed using the formula:

$$P_j = M_j \bullet w_j \quad (W) \qquad 1.$$

where, P_j = instantaneous power at joint j in watts,
M_j = net moment of force at joint j in N•m,
w_j = relative angular velocity of joint j in rad/s.

The sign, positive or negative, of the net joint moment of force indicated which musculature, flexor or extensor, respectively, was dominant at a particular time. Note that a net moment of force does not tell whether the tissues were performing positive or negative work or were working isometrically. It simply shows the magnitude and direction of the net effect of all the muscles and other structures that created moments of force across a particular joint producing the observed kinematic pattern. In general, a net moment of force is caused almost wholely by skeletal muscle contractions if the range of joint movement is not excessive, but ligaments, skin and the joint capsule can also contribute to the moment production. The sign of the instantaneous power, positive or negative, indicated what type of contraction, either concentric or eccentric, produced the net joint moment.

Joint Work. The net mechanical work performed at each joint was calculated by integration of the power history of the joint (Bresler and Berry, 1951; Cappozzo et al., 1976; Hubley and Wells, 1983; Robertson, 1985; Robertson and Mosher, 1985; White and Winter, 1985; Winter, 1983; Zarrugh, 1981). In this study trapezoidal integration was used. The work done was determined for two time periods. First the joint work was computed for the entire jump (e) from the beginning (beg) of downward movement through to the time when the toes left the force platform (to). Second the work done was calculated for the propulsive phase (p) of the jump, from the start of upward movement (um) to toe-off (to). The following equation was used:

$$W_{j(e)} = \int_{beg}^{to} P_j \bullet dt \qquad (J) \qquad 2.$$

where, W_j = mechanical work done at joint j in joules.

The sign of the joint work indicates whether the muscles crossing the joint were net generators (positive) or absorbers (negative) of energy during the particular time intervals examined.

The total work done at the joints (TJW) for both the entire jump and the propulsive phase of the jump was determined by summing the work done by the individual joints:

$$TJW_{(e)} = \sum_{j=1}^{6} W_{j(e)} \quad (J) \qquad 3.$$

<u>Energy Calculations</u>. The total body gain in energy (TBE) was also calculated for both the entire jump and the propulsive phase of the jump. It was obtained by taking the difference between the sum of the energy values for all the segments (TSE) at toe-off and the sum of the segment energies at the beginning of the time interval of interest.

$$TBE_{(e)} = TSE \Big|_{beg}^{to} = TSE_{(to)} - TSE_{(beg)} \quad (J) \qquad 4.$$

The total segment energy was found by summing the energies of the individual segments. The individual segment energy (SE) was the total of the segment's potential, translational kinetic and rotational kinetic energy values.

$$TSE = \sum_{s=1}^{7} SE_s \quad (J) \qquad 5.$$

$$SE_s = m_s g h_s + \frac{1}{2} m_s v_s^2 + \frac{1}{2} I_s w_s^2 \quad (J) \qquad 6.$$

where, m_s = mass of segment s in kg,
g = gravitational acceleration (9.81 m/s^2),
h_s = height of the center of mass of segment s in m,
v_s = absolute linear velocity of the center of mass of segment s in m/s,
I_s = moment of inertia about the center of mass of segment s in $kg \cdot m^2$,
w_s = absolute angular velocity of segment s in rad/s.

Work-Energy Analysis. The ratio of the work done at all the joints (TJW) to the total body energy gain (TBE) was calculated for both the entire jump and for the propulsive phase of the jump for the two types of jumps. This was done to check the accuracy of the analysis techniques (cf., Hubley and Wells, 1983). The TBE was taken as the criterion measure because it was dependent upon first derivative displacement-time data that was easily obtained and also because it assumed that the segments acted independently of one another (Quanbury et al., 1975; Robertson and Winter, 1980). On the other hand, the TJW required joint force and torque values that relied on second derivative information (Quanbury et al., 1975). As well, the joint force and torque values from the more distal joints were utilized in the determination of the net force and torque at the more proximal joints. Hence, any errors in distal joint force or moment of force calculations would be passed along to subsequent proximal joints in the kinematic chain.

Joint Contribution. The absolute contribution of the individual joint work to increasing the total body energy was arrived at by calculating the ratio of individual joint work to TBE. The relative contribution of the individual joints to the TJW was found by normalizing the absolute work done at each joint with respect to the TJW. As well, the relative contribution of the work done by the leg joints alone was determined by dividing the absolute work values for each leg joint by the total work done at all three leg joints. This was done in order that a comparison could be made with the results of Hubley and Wells (1983) and Robertson and Fleming (1986). All of the above calculations were made for both types of jumps over the entire jump and propulsive phase of each jump.

Statistics. Two-tailed correlated t-tests, with $p \leq .05$ chosen as the level of significance, were used to check for occurrences of significant differences in individual joint work contribution to the standing jumps during the two time intervals examined. Since relative percent contribution to the total work done at the leg joints was the measurement utilized, only two leg joints could be examined as there were only two degrees of freedom. The ankle and the knee joints were chosen for analysis because it was assumed that if the accuracy of the joint work results decreased, it would decrease from the distal to the proximal leg joints. This assumption was based on the fact that the link segment analysis started at the toe and moved proximally to the hip joint. Therefore, any errors in link segment modelling or in joint moment calculations would subsequently affect the results at the more proximal joints. Four tests were done, two each for the ankle and knee joints. Only the results of the six subjects which had both a vertical jump and standing broad jump analyzed were used for the correlated t-tests.

Four one-way ANOVAs with repeated measures were done to test the differences between relative joint contributions for each type of jump. Two were utilized for the standing broad jump (n=6), looking at the propulsive phase and the entire jump, and two for the vertical jump (n=12). Neuman-Keuls post hoc procedure was used to evaluate the multiple pairwise comparisons. The significance level for the ANOVAs and the Neuman-Keuls comparisons was again $p \leq .05$.

Principle Evaluation. A determination of the validity of the principles of summation and continuity of joint forces with respect to standing broad and vertical jumps was made. It was assumed that both principles only applied during the propulsive phase of jumping. The criterion that was established to test the summation principle for standing broad and vertical jumping was that the net mechanical work done by the moments of force at the three leg joints must be positive for all joints during the propulsive phase of jumping. For the continuity principle it was felt that looking at both the power and moment curves would be more informative than simply looking at the moment curves alone because by themselves the moment curves did not indicate when a moment of force contributed to a jump. It was determined that the contribution of a joint to the jump began at the time when the instantaneous power curve became positive as a result of an extensor moment at that joint during the propulsive phase of jumping. In the case where the instantaneous power curve was positive more than once during the propulsive phase due to an extensor moment, the beginning of the first phase that accounted for at least 25 percent of the positive work done at the joint during the propulsive phase was used to indicate the time of the power contribution for the joint. The sequencing of the power contributions from the leg joints had to have a proximal to distal ordering for the continuity principle to hold. Simultaneous power contributions from two or three joints precluded the continuity principle from holding as did a sequencing that was not from proximal to distal.

Performance Analysis. Finally, a performance analysis was done on all analyzed jumps to give an indication of the jumping ability of the subjects involved in the study. Using equations of motion incorporating kinematic data relating to the body center of gravity, a predicted distance that the body center of gravity would move either vertically (vertical jump) or horizontally (standing broad jump) was determined for each subject. As well, the relevant ground reaction forces for the standing broad jump and vertical jump were normalized in terms of each subject's body weight to give an indication of the appropriateness of the force plate data.

RESULTS

(Note: The means for standing broad jump data in Tables 2-7, 10 and 12 are for an n=6 while the vertical jump means in the same tables are for an n=12.)

Tables 2 and 3 contain the relative contributions of each leg joint to the total work done by the legs for the two types of jumps during the entire jump and the propulsive phase of jumping, respectively. Tables 4 and 5 list both the absolute and relative contribution of all six joints to the gain in total body energy for standing broad jumping during the entire jump and the propulsive phase, respectively. Tables 6 and 7 do the same for the vertical jump. In all cases a positive value indicates that the joint was a net generator of energy for the time period examined while a negative value means that the joint was a net dissipator of energy.

In Tables 4 through 7 the mean ratio of work done at the joints (TJW) to the energy gained (TBE) represents the results of the work-energy analysis for the two kinds of jumps over the two time intervals of interest. Since the TJW-TBE ratio is less than 1.000 in all four conditions, then, on average, the TJW did not account for all the gain in TBE.

In Table 8 are presented the results of the statistical analysis on relative ankle and knee joint contribution to the work done at the leg joints for the two types of jumps both during the propulsive phase and over the entire jump.

The means for relative joint contribution during the propulsive phase of vertical jumping for the six subjects who had both a standing broad jump and a vertical jump analyzed were 38.8 $\pm$ 4.2 percent (ankle), 21.5 $\pm$ 18.5 percent (knee) and 39.7 $\pm$ 15.5 percent (hip). Over the entire vertical jump the ankle, knee and hip means were 32.2 $\pm$ 4.7, 23.8 $\pm$ 8.1 and 44.0 $\pm$ 10.0 percent, respectively, for the same subjects. Of the four correlated t-tests done, the only significant difference occurred in the ankle joint for the entire jump. This difference favored the vertical jump. Therefore, over the entire jump relatively more work was done at the ankle joint in vertical jumping than in standing broad jumping. Table 8 also shows non-significant differences for the contribution of the ankle joint to the jumps during the propulsive phase and for the contribution of the knee joint to the two jumps during both time intervals.

The results of all the pairwise comparisons relating to the four ANOVAs are listed in Table 9. The work values being compared are those listed in Tables 2 and 3. The muscles crossing the hip joint did significantly more work than those of the knee joint during both standing broad ($p<.01$) and vertical jumping ($p<.05$) when the jumps were looked at in their entireties. For the propulsive phase, there was significantly more work generated at the hip joint than at either of the other two leg joints during both vertical (knee: $p<.01$; ankle: $p<.05$) and standing broad jumping (knee: $p<.01$; ankle: $p<.01$). A significant difference ($p<.05$), favoring the ankle joint, also occurred during the entire vertical jump when the work done at the ankle and knee joints was compared. During the propulsive phase and over the entire jump in standing broad jumping, the differences between relative ankle and knee joint contributions were non-significant. As well there was a non-significant difference between relative ankle and knee joint contributions during the propulsive phase of vertical jumping. Over the entire jump in both standing broad and vertical jumping there were no significant differences between the relative hip and ankle joint contributions to the total work done at the leg joints.

Table 10 presents a summary of the various work phases that each jumper exhibited during vertical and standing broad jumping. Other work episodes were also present for some jumpers. However, the phases that are listed in Table 10 are those that were consistent for all subjects. In both kinds of jumps all subjects exhibited two types of ankle muscle activity, labelled A1 and A2, three types of knee muscle activity, labelled K1, K2 and K3, and three types of hip muscle activity, H1, H2 and H3. In addition the standing broad jump had a fourth identifiable type of hip muscle activity labelled H4. K3 and H4 were episodes that both started before toe-off and continued after toe-off. The means and standard deviations of the work done by the various types of contractions are also listed in Table 10.

As well the footnotes at the bottom of Table 10 explain the codes used in the table, identifying the joint involved, the dominant muscle group and the type of contraction responsible for a particular work episode.

Figure 1 gives a pictorial account of the time sequence of muscular contractions at the hip, knee and ankle joints for the standing broad and vertical jumps. The appropriate codes (Tables 10) are used to label the beginning of particular work phases. The start of the propulsive phase for each type of jump is indicated by the vertical line labelled P. Figure 1 shows that the standing broad jump took longer to perform than the vertical jump. In spite of this, the propulsive phases of each jump are almost identical in length.

Figures 2, 3 and 4 show one jumper's ankle, knee and hip kinematics and kinetics for standing vertical jumping while Figures 5, 6 and 7 show another jumper's ankle, knee and hip kinematics and kinetics for standing broad jumping. The top graph in each figure represents the relative angular velocity of the joint. The middle graph is the net moment of force history with labels identifying the dominant muscle group. Lastly, the bottom graph is the power produced by the net moment of force with labels specifying the type of contraction occurring in the dominant muscle group. All six figures have the same abscissa and ordinate scaling for comparative purposes. As well, the appropriate work phases, as designated in Table 10, are indicated on the power curves in Figures 2 through 7.

The degree of support for the principles of summation of joint forces and continuity of joint forces during standing broad and vertical jumping is indicated by the results in Table 11. The numerator of the ratios represents the number of trials analyzed where the principle was in evidence while the denominator is the total number of trials analyzed. One vertical jump for each of the twelve subjects was analyzed but only six of the subjects had standing broad jumps that could be used.

An indication of the performance capabilities of the subjects is presented in Table 12. Variable d1 is the distance the body center of gravity moved in the vertical or horizontal directions from initial standing on the force plate to toe-off for the vertical or standing broad jumps, respectively. The predicted distance the body center of gravity would move after toe-off, in the vertical direction for the vertical jump and the horizontal direction for the standing broad jump, is given by d2. Lastly d3, where d3 = d1+d2, gives the predicted distance, either vertically or horizontally, that the body center of gravity would move altogether for the vertical jump or standing broad jump, respectively.

A check of the ground reaction force data revealed that the peak vertical force averaged 2.70 $\pm$ 0.30 times body weight for the vertical jump. The peak vertical and horizontal forces for the broad jump were 2.21 $\pm$ 0.34 and 1.05 $\pm$ 0.14 times body weight, respectively.

Table 2. Average relative contribution of the leg joint moments to the total work done at the leg joints during the entire jump

Joint	Broad Jump	Vertical Jump
Ankle	31.5 $\pm$ 3.4 %	39.2 $\pm$ 8.9 %
Knee	17.0 $\pm$ 15.3	22.4 $\pm$ 14.9
Hip	51.5 $\pm$ 13.4	38.4 $\pm$ 11.3

Table 3. Average relative contribution of the leg joint moments to the total work done at the leg joints during the propulsive phase

Joint	Broad Jump	Vertical Jump
Ankle	30.2 $\pm$ 7.2 %	33.0 $\pm$ 6.6 %
Knee	18.6 $\pm$ 8.3	24.8 $\pm$ 8.3
Hip	51.2 $\pm$ 9.5	42.2 $\pm$ 10.0

Table 4. Average absolute and relative joint contribution to the gain in total body energy for the entire jump in standing broad jumping

Joint	Absolute	Relative
Ankle	25.7 ± 5.6 %	27.4 ± 2.9 %
Knee	13.8 ± 12.6	15.0 ± 13.4
Hip	41.5 ± 12.3	44.8 ± 11.4
Elbow	6.2 ± 1.9	7.0 ± 2.8
Shoulder	5.0 ± 4.1	5.4 ± 4.7
Neck	0.6 ± 1.6	0.4 ± 1.6
TJW/TBE	0.928 ± 0.124	1.000

Table 5. Average absolute and relative joint contribution to the gain in total body energy during the propulsive phase of standing broad jumping

Joint	Absolute	Relative
Ankle	26.4 ± 6.3 %	30.9 ± 7.5 %
Knee	16.2 ± 7.1	19.0 ± 8.5
Hip	45.3 ± 11.1	52.6 ± 10.1
Elbow	3.8 ± 0.7	4.5 ± 1.1
Shoulder	-5.8 ± 3.4	-6.7 ± 3.8
Neck	-0.2 ± 0.8	-0.3 ± 1.0
TJW/TBE	0.856 ± 0.086	1.000

Table 6. Average absolute and relative joint contribution to the gain in total body energy for the entire jump in vertical jumping

Joint	Absolute	Relative
Ankle	28.9 ± 8.1 %	35.5 ± 8.2 %
Knee	16.0 ± 10.2	20.3 ± 13.3
Hip	28.7 ± 9.5	34.8 ± 10.4
Elbow	6.5 ± 2.7	8.0 ± 3.3
Shoulder	2.1 ± 4.6	2.3 ± 6.1
Neck	-0.7 ± 1.3	-0.9 ± 1.5
TJW/TBW	0.814 ± 0.118	1.000

Table 7. Average absolute and relative joint contribution to the gain in total body energy during the propulsive phase of vertical jumping

Joint	Absolute	Relative
Ankle	26.5 ± 6.1 %	33.1 ± 7.1 %
Knee	20.2 ± 7.4	24.7 ± 8.1
Hip	34.1 ± 8.9	42.3 ± 10.3
Elbow	3.8 ± 1.7	4.8 ± 2.4
Shoulder	-3.4 ± 3.9	-4.4 ± 4.9
Neck	-0.4 ± 0.7	-0.5 ± 0.9
TJW/TBW	0.808 ± 0.093	1.000

Table 8. Comparison of the relative percent contribution of the ankle and knee joints in vertical jumping to their contributions in standing broad jumping

Joint	Propulsive Phase	Entire Jump
Ankle	n.s.	$p<.01$
Knee	n.s.	n.s.

Table 9. Comparison of relative joint contributions

	BROAD JUMP		VERTICAL JUMP	
Joint Comparison	Propulsive Phase	Entire Jump	Propulsive Phase	Entire Jump
Hip-Knee	$p<.01$	$p<.01$	$p<.01$	$p<.05$
Hip-Ankle	$p<.01$	n.s.	$p<.05$	n.s.
Ankle-Knee	n.s.	n.s.	n.s.	$p<.05$

Table 10. Average work done by contractions of the muscles crossing the ankle, knee and hip joints

Phase	Broad Jump	Vertical Jump
* A1	-23.4 ± 13.5 J	-25.0 ± 11.3 J
A2	165.6 ± 41.2	173.5 ± 35.4
K1	-44.4 ± 31.8	-65.3 ± 39.8
K2	114.0 ± 27.9	164.3 ± 36.5
K3	-13.7 ± 7.6	-29.5 ± 17.2
H1	25.4 ± 12.5	29.8 ± 16.2
H2	-156.4 ± 36.1	-133.2 ± 46.3
H3	357.8 ± 79.3	258.6 ± 86.5
H4	-17.6 ± 11.9	-----

* These codes indicate the following types of muscle contractions:

A1	Plantar flexor eccentric
A2	Plantar flexor concentric
K1	Knee extensor eccentric
K2	Knee extensor concentric
K3	Knee flexor eccentric
H1	Hip flexor concentric
H2	Hip extensor eccentric
H3	Hip extensor concentric
H4	Hip flexor eccentric

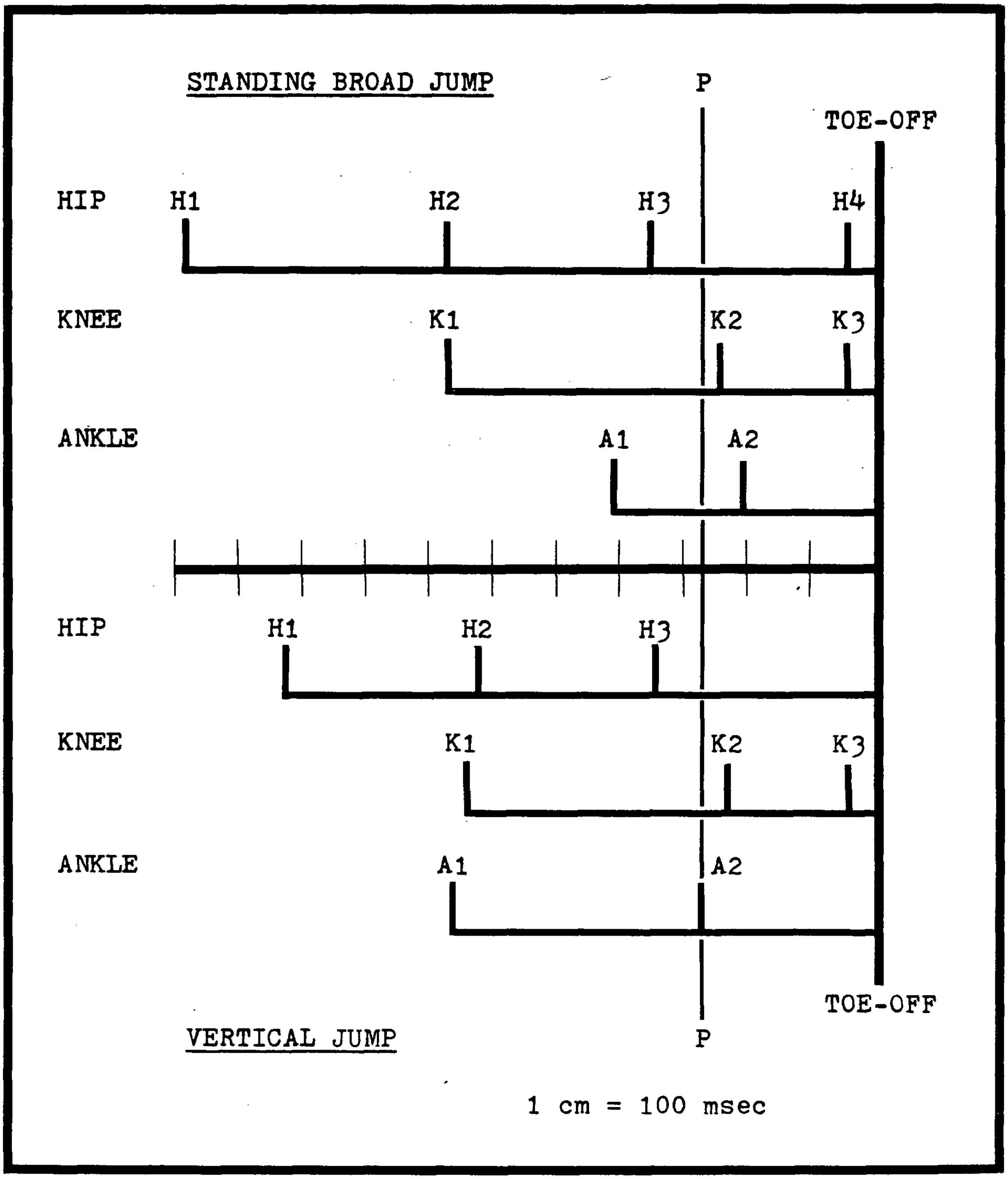

Figure 1. Sequencing of muscular contractions for standing broad and vertical jumping (P = start of the propulsive phase)

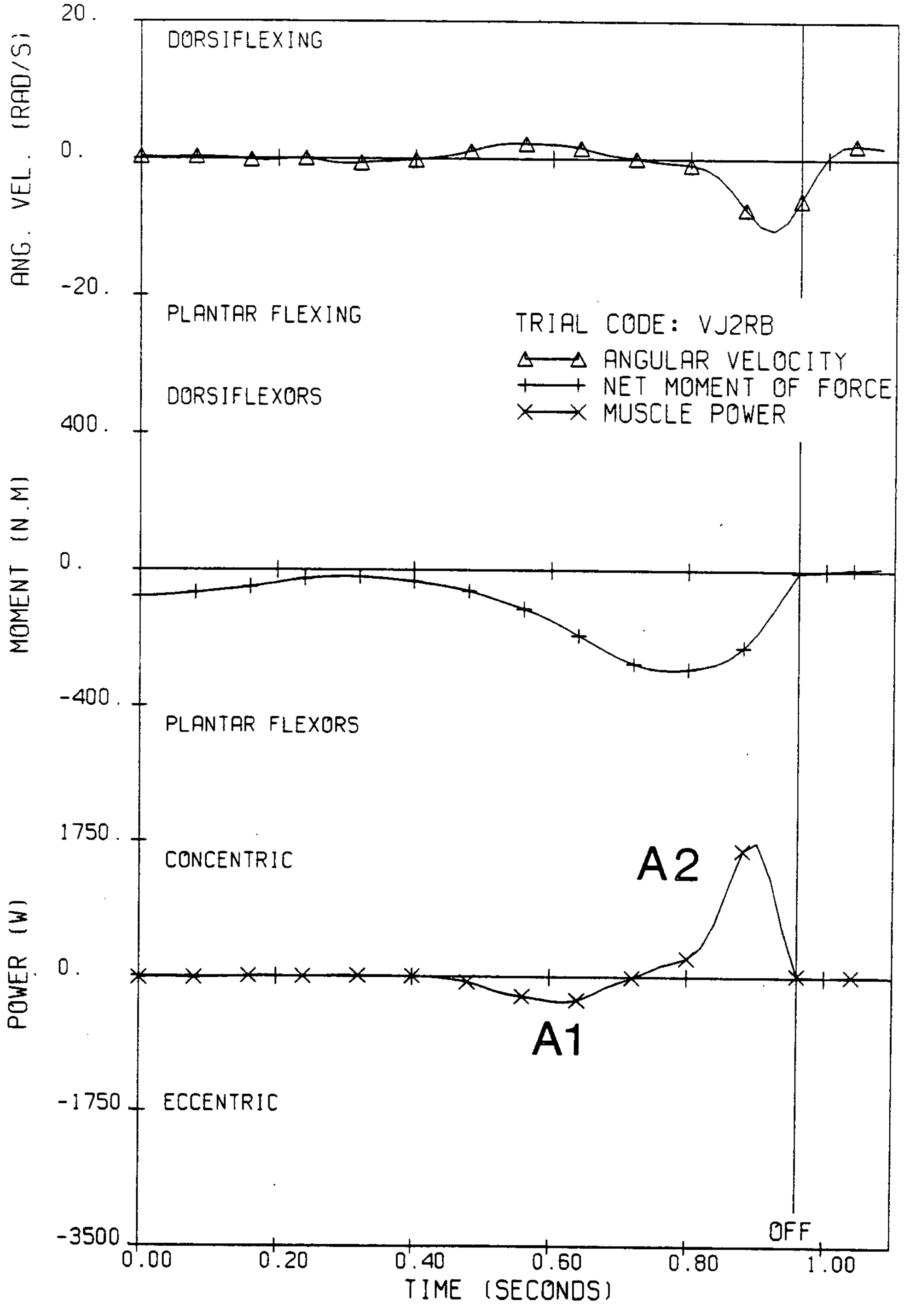

Figure 2. Ankle plots for vertical jumping

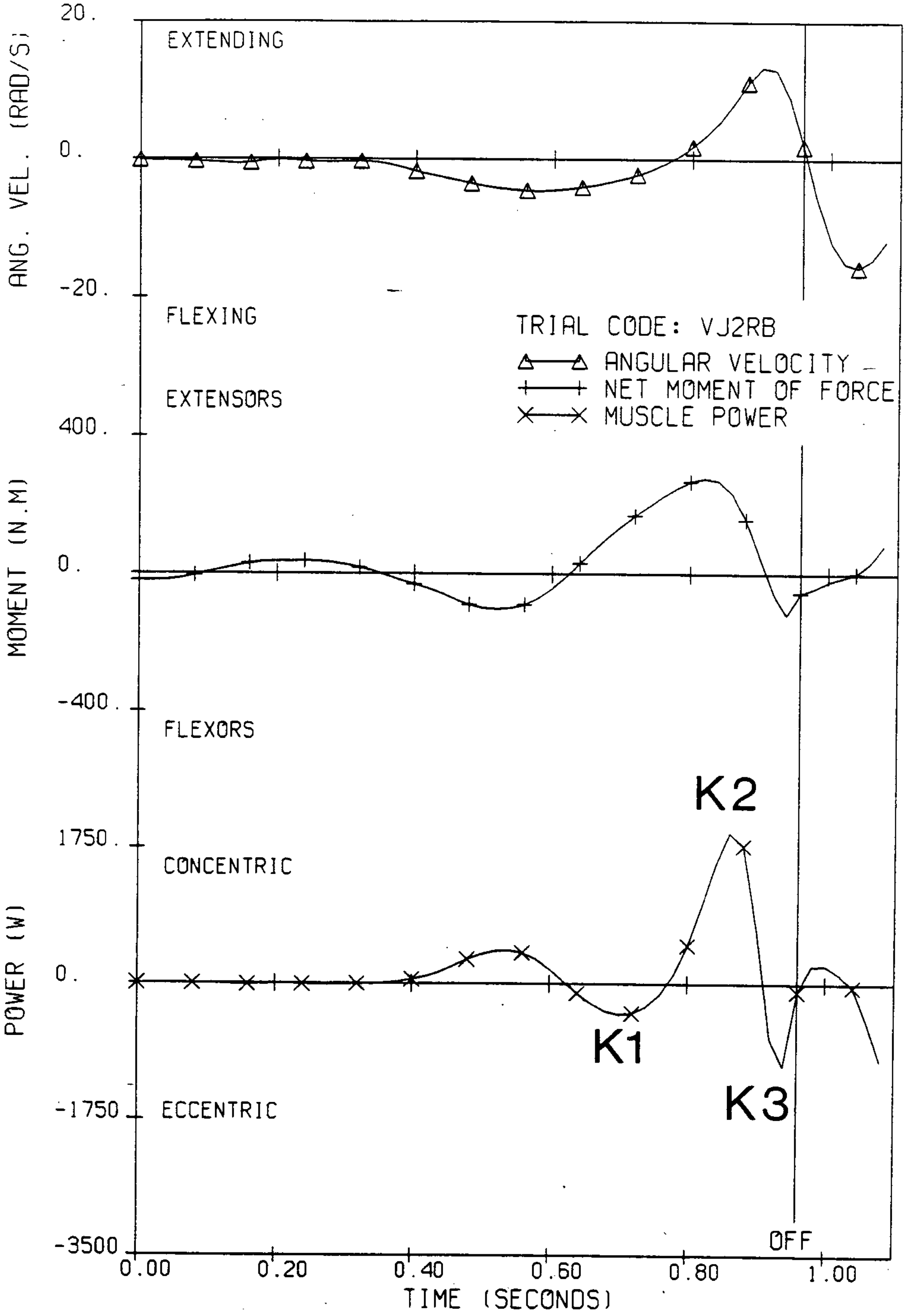

Figure 3. Knee plots for vertical jumping

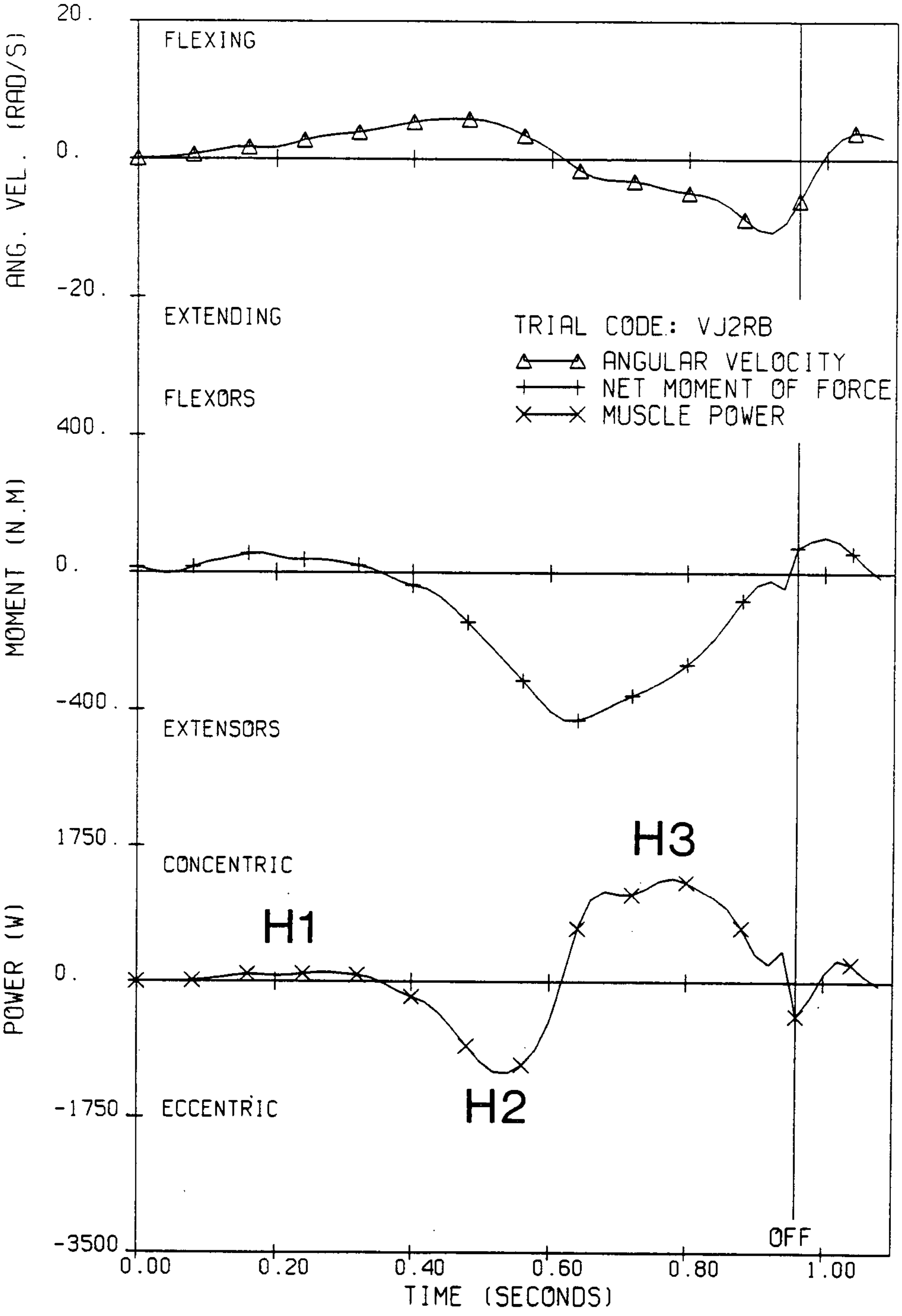

Figure 4. Hip plots for vertical jumping

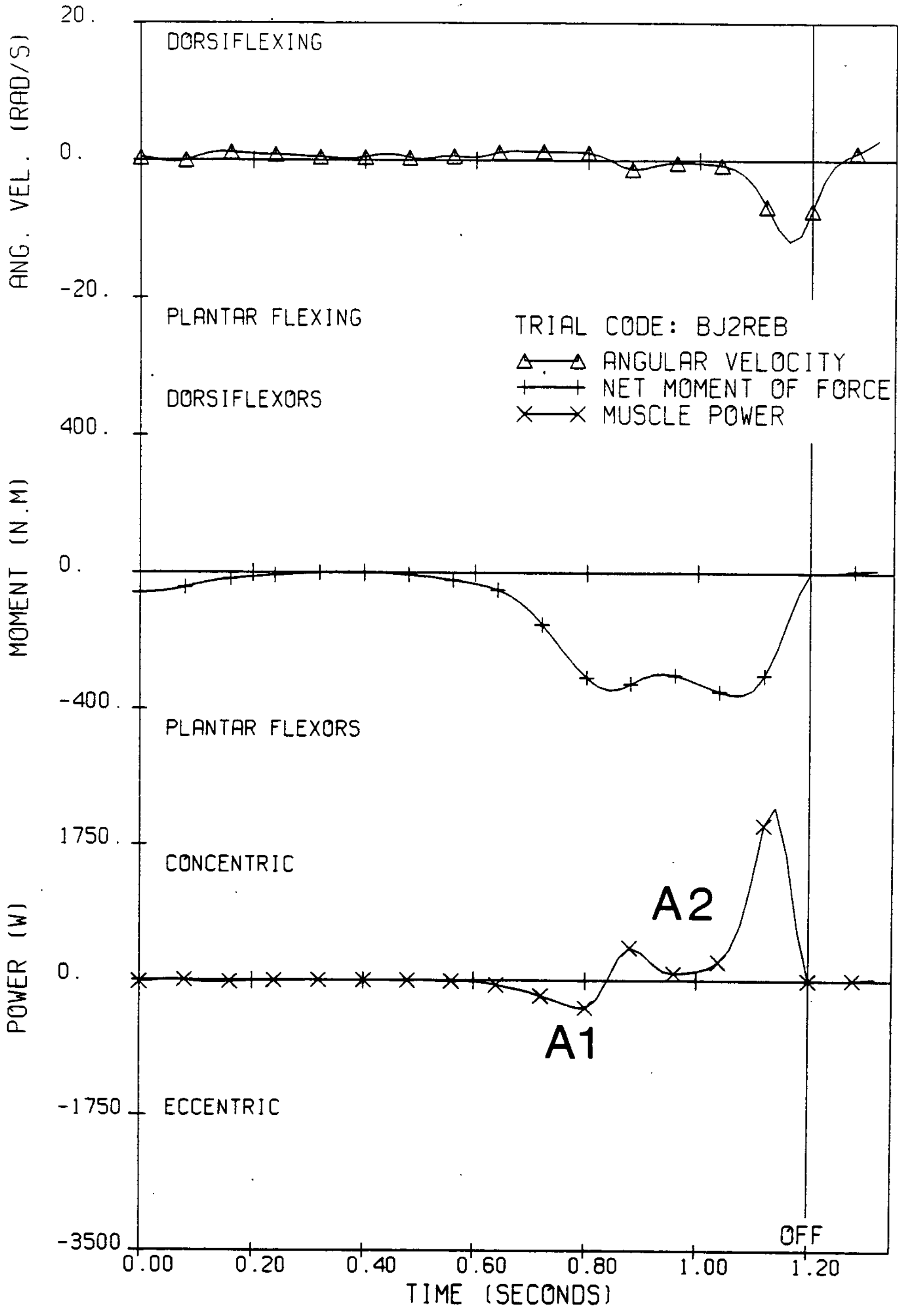

Figure 5. Ankle plots for standing broad jumping

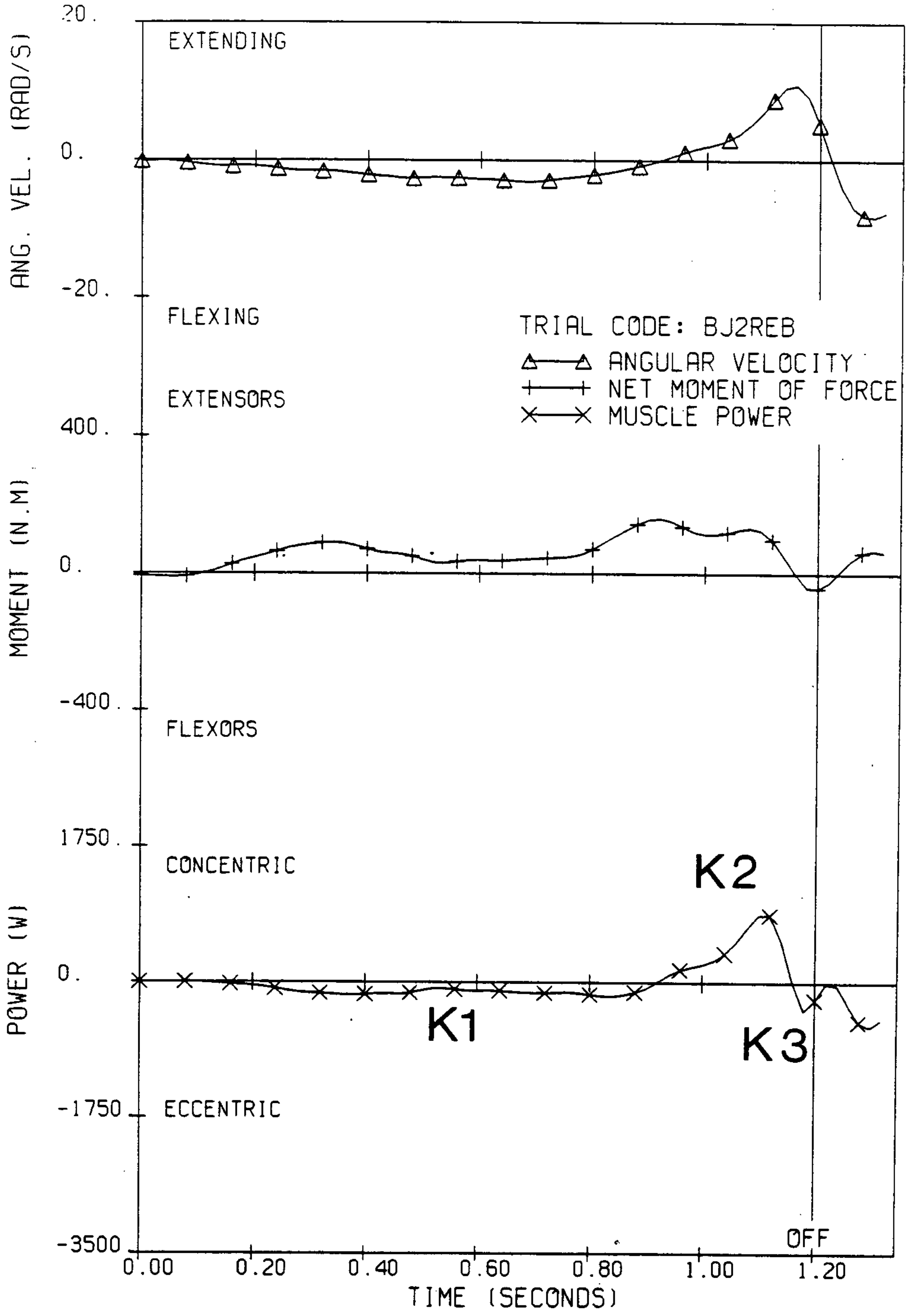

Figure 6. Knee plots for standing broad jumping

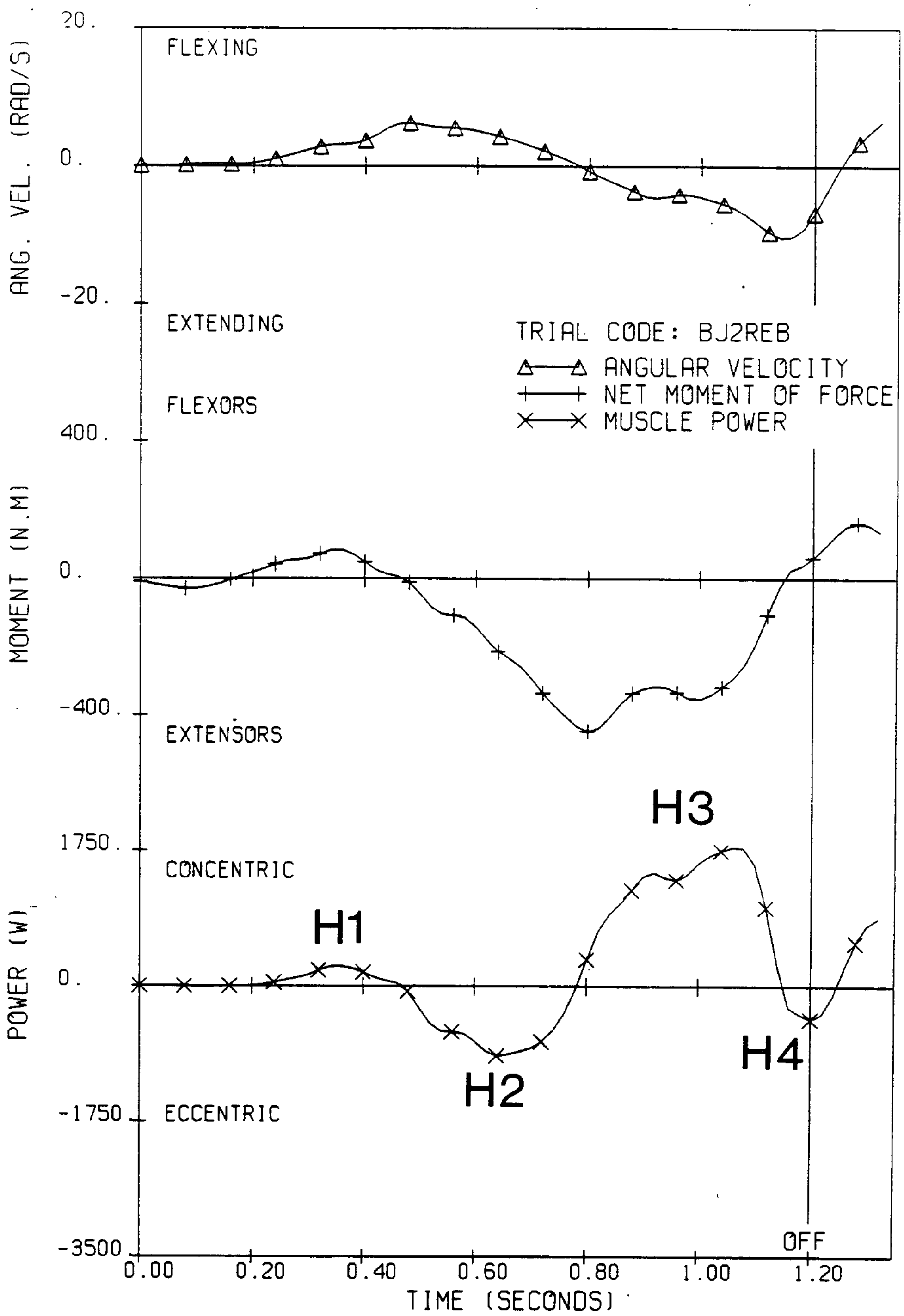

Figure 7. Hip plots for standing broad jumping

Table 11. Indication of the extent of support for the summation and continuity principles

Principle	Broad Jump	Vertical Jump
Summation	6/6	12/12
Continuity	3/6	2/12

Table 12. Predicted performance of subjects

Distance	Broad Jump	Vertical Jump
d1	0.832 ± 0.053 m	0.157 ± 0.024 m
d2	2.160 ± 0.159	0.485 ± 0.068
d3	2.992 ± 0.162	0.642 ± 0.075

DISCUSSION

LEG JOINT WORK

Standing Broad Jump. The results for the standing broad jump (Tables 2 and 3) indicate that the muscles of all three leg joints were net generators of energy during both the entire jump and the propulsive phase of standing broad jumping. In both cases the percentage contributions of the three leg joints were very similar. The work done by the muscles crossing the hip joint accounted for just more than half of the work done at the leg joints. The ankle joint was the next largest work contributor while the knee joint had the smallest work output.

These results differ from those of Robertson and Fleming (1986) who limited themselves to looking at relative leg joint contribution during the propulsive phase. They found that the contributions of the muscles crossing the hip, knee and ankle joints to the work done by the legs were 45.9, 3.9 and 50.2 percent, respectively. Subsequent analysis of their data to get leg joint contributions for the entire jump yielded percentages of 44.8 for the hip, -4.2 for the knee and 59.4 for the ankle. The -4.2 percent for the knee joint indicated that the muscles of the knee were net dissipators of energy during the standing broad jump. For both the entire jump and the propulsive phase, the largest contributor to the work done by the leg joints was the ankle in the Robertson and Fleming (1986) study.

Furthermore, the knee was the least important joint as far as generating positive work was concerned.

There may be several overlapping reasons for the differences in results between the present study and those of Robertson and Fleming (1986). In the current study the subjects were allowed to use their arms while subjects in the study by Robertson and Fleming (1986) were restricted in performing the jump by keeping the hands on the hips. Since that is not the typical way to perform the vertical jump, it may be that some alteration in leg joint involvement occurred to compensate for the unusual movement pattern. This change in movement pattern may have been sufficient enough cause to reduce or inhibit the contribution of the hip muscles and to increase or enhance the contribution of the muscles crossing the ankle joint. Another factor that conceivably accounts for the difference in results is that the peak horizontal forces in the Robertson and Fleming (1986) study averaged only 0.65 times body weight. From Roy et al. (1973), one would expect the peak horizontal force to approximate body weight. This was the case in the present study. The underestimation of the horizontal ground reaction forces in the investigation by Robertson and Fleming (1986) would lead to errors in the calculations of reaction forces and moments of force at all three leg joints and would directly affect the joint work values.

Another potential cause for the contrasting results is that the manner in which athletes of varying capabilities produce work may differ. The subjects involved in the current study were specifically chosen because they were better than average jumpers. This point is supported by their predicted performance (2.992 m) in the standing broad jump when compared to the predicted performance (2.152 m) of the subjects in the Robertson and Fleming (1986) investigation. A confounding variable here is the sex of the subjects involved in the two studies. It must be noted that only two of the six subjects in the research of Robertson and Fleming (1986) were male while all six standing broad jump subjects in the present study were male. The predicted performance of both male subjects (2.430 m) in the Robertson and Fleming (1986) investigation was better than that of their four female counterparts (2.013 m), but it was well below the predicted performance of the subjects in the current study. Therefore, as far as standing broad jumping is concerned, there was definitely a discrepancy in the performance capabilities of the male subjects involved in the two studies. No conclusion can be made about the capabilities of the four female subjects in the study by Robertson and Fleming (1986) because no information for comparison was found in the literature on jumping.

Regarding the low contribution of the muscles crossing the knee joint which was found in the two studies, other researchers who have studied movements that were primarily concerned with horizontal displacement of the body and which contained a double leg support phase also noticed the lack of importance of the knee joint in doing positive work. Bresler and Berry (1951), Cappozzo *et al*. (1976) and Zarrugh (1981), in looking at walking, and White and Winter (1985), when examining race walking, found that for one stride of each activity the muscles crossing the ankle and hip joints generated more energy than they received while the opposite was true for the muscles of the knee joint. None of these studies calculated the relative leg joint contributions.

Vertical Jump. From the vertical jump results (Table 2 and 3), it can be seen that all three leg joints contributed to vertical jumping over the entire jump and during the propulsive phase. There was a slight difference between the relative leg joint contributions for the entire jump and for the propulsive phase. Over the entire jump both the ankle and hip joints contributed almost equally to the work done at the leg joints while for the propulsive phase the muscles crossing the hip joint were the major net generators of energy. For both the entire jump and the propulsive phase of vertical jump the contribution of the knee joint to the positive work done at the leg joints was very similar.

Robertson and Fleming (1986) have also looked at the propulsive phase of vertical jumping as did Hubley and Wells (1983). The leg joint contributions of 40.0 percent for the hip, 24.2 percent for the knee and 35.8 percent for the ankle that Robertson and Fleming (1986) found were very close to the results of the present study. On the other hand, Hubley and Wells (1983) obtained substantially different percentages of 27.5, 49.0 and 23.5 for the muscles of the hip, knee and ankle joints, respectively, during the propulsive phase of countermovement jumping. They also looked at squat jumping and obtained contributions almost identical to those achieved in countermovement jumping. In their study then, the knee joint was the biggest generator of energy for the legs.

One cause of the discrepancy in results between the research of Hubley and Wells (1983) and both the current study and that of Robertson and Fleming (1986) is the performance level of the subjects. The predicted rise in the body center of gravity after toe-off (d2 in the present study) for the six male subjects in the Hubley and Wells (1983) investigation averaged only 33 cm (from Hubley, 1981) which is well below the 40.3-43.4 cm range achieved by male subjects in other studies (Asmussen and Bonde-Petersen, 1974; Bosco and Komi, 1979; Komi and Bosco, 1978a, 1978b) and the one male vertical jump subject (42.8 cm) in the Robertson and Fleming (1986) investigation. Since all of these studies restricted arm movements during countermovement jumping, the performance of the subjects can be compared. Hence the conclusion that the subjects used by Hubley and Wells (1983) were poorer jumpers than the subjects in the other studies. Another area of concern is the force plate. Hubley and Wells (1983) neglect to provide information about the characteristics of their force plate so its quality cannot be ascertained, thus leaving doubts about the accuracy of their data.

The other side of the coin sees the results of the present investigation and those of Robertson and Fleming (1986) being very similar despite both the fact that Robertson and Fleming (1986) restricted the use of the arms and that the performance capabilities of the subjects in that study, as measured by both predicted performance (0.501 m) and peak vertical force (2.28 times body weight), were lower than those of the subjects involved in the present investigation. However, the differences in performance capabilities of the subjects in the two studies are not as great as they initially appear for two reasons. First, it was to be expected that the average peak vertical force would be less in the Robertson and Fleming (1986) study, although probably not quite to the extent that it was. This is due to the fact that when Payne et al. (1968) looked at ground reaction forces during performance of standing vertical jumps, they noticed that use of the arms created a greater peak on the impulse curve than vertical jump performance where use of the arms was restricted. The second apparent reason is the sex of the subjects. Two of the three subjects for Robertson and Fleming (1986) were female while only one of the twelve subjects in the current investigation was female. The predicted vertical jump performance of the male subject (62.0 cm) and the female subjects (44.1 cm) for Robertson and Fleming (1986) compare reasonably well to the male subjects (65.6 cm) and one female subject (49.1 cm) of the present study.

Further analysis of the Robertson and Fleming (1986) data revealed leg joint contributions over the entire vertical jump of 40.1 percent for the hip, 18.5 percent for the knee and 41.3 percent for the ankle. These were, again, very similar to the results found in the present study. In spite of the similarity in results between the two studies it is difficult to state with any conviction that the similarity is due to an established trend in both investigations because of the small sample size (n=3) for the vertical jump in the Robertson and Fleming (1986) study.

While patterns of joint contribution emerged in the current study for both standing broad and vertical jumps, the fairly large inter-subject variability exhibited at all the leg joints, with the exceptions of the ankle joint over the entire standing broad jump, indicate that the manner in which subjects used the major leg muscle groups to generate work was quite variable. This finding is supported by the data of Hubley and Wells (1983) and Robertson and Fleming (1986) who also obtained relatively large standard deviations for most of the leg joints. The variability in leg joint contribution also points out the difficulty in establishing the importance of one group of leg extensors as the dominant muscle group for jumping.

Statistics. The results of the four correlated t-tests (Table 8) show that, relatively, the muscles crossing the knee joint contributed the same amount of work to both the standing broad and vertical jumps, and that over the entire jump the relative contribution of the muscles of the ankle joint to the work done at the leg joints was significantly greater in the vertical jump than for the standing broad jump. Kinesiologists have assumed that various skills involving the same musculature utilize the musculature differentially and physiologists, through the principle of specificity, have expressed the same opinion. The one significant result of this present study partially reinforces that idea for two different jumping movements.

From Tables 2, 3 and 9, it can be seen that for all four conditions the relative contribution of the muscles crossing the hip joint to the work done at all three leg joints was significantly greater than the contributions of the knee muscles. As well, during the propulsive phase of both standing broad and vertical jumping, the relative amount of work done at the hip joint was significantly greater than the the work done at the ankle joint. However, over the entire jump there was no significant difference between the relative amounts of work done at the hip and ankle joints. This is because the work phase H2 (Table 10) dissipates a large amount of energy prior to the start of the propulsive phase. Modification of the vertical jump by restricting trunk extension to isolate leg power, i.e. the contribution of the muscles crossing the knee and ankle joints, is not an uncommon practice. It is based on the assumption that the knee musculature is the major contributor to the work done in jumping. But the significant results favoring the hip joint in this study indicate that restriction in hip joint movement actually reduces the contribution of a major source of power in the legs.

Summary. The results for individual leg joint contribution reveal that, over the entire jump, standing broad jumping utilizes the muscles of the ankle joint differently than vertical jumping. They also show the importance of the hip musculature in the production of work in jumping, particulary during the propulsive phase. This finding contradicts the assumption that the knee muscles are the major contributor to the work done in jumping.

OTHER JOINT WORK

Tables 4 to 7 list the absolute and relative contributions of the six joints during the entire jump and the propulsive phase of both standing broad and vertical jumping. Beside the leg joints, the elbow was the only other joint that was a net generator of energy for both types of jumps over the two time intervals of interest. The shoulder joint was a net generator of energy for both types of jumps over the entire jump but a net absorber of energy during the propulsive phase of jumping. The muscles of the neck joint accounted for an insignificant amount of the energy developed or dissipated in all cases. For both types of jumps, the upper body joints tended to contribute to the work done over the entire jump but cancelled out one another during the propulsive phase.

WORK-ENERGY ANALYSIS

The work-energy ratios presented in Tables 4 to 7 show that the work done at the individual joints did not account for all the gain in total body energy at toe-off. This result is similar to that of Robertson and Fleming (1986) who reported work-energy ratios of 0.953 and 0.872 for the propulsive phase of vertical and standing broad jumping, respectively. Subsequent analysis of their data over the entire jump gave ratios of 1.312 for the vertical jump and 1.317 for the broad jump. The results of both the current investigation and those of Robertson and Fleming (1986) oppose those of Hubley and Wells (1983) who had very good agreement between their work and energy values for the propulsive phase of both countermovement and squat jumping.

Since the work-energy ratios were less than 1.000 it must be assumed that there are other sources of work that subjects were using and which were not measured in this analysis. The appropriateness of the model used for analysis of all subjects becomes questionable in light of the fact that 9 of 12 subjects for both the propulsive phase and the entire jump in vertical jumping, and 3 of 6 subjects over the entire jump and 4 of 6 subjects during the propulsive phase for the broad jump had work-energy ratios calculated to be greater than 10 percent above or below

1.000. There may have also been systematic errors in the modelling of the human body or in the data collected.

Pezzack and Norman (1981) in their paper on validation of joint and moment output of multi-segment linkages mentioned several concerns about link segment modelling. They noted that errors in body segment accelerations confounded the calculation of joint moments and reaction forces because the errors accumulated in complex (greater than six segments) multi-segment linkages. They also suspected that there were large errors at the hip and shoulder where the arms and legs attached to the trunk, although they failed to state what these errors could possibly be. As well Pezzack and Norman (1981) had trouble in achieving consistent trunk length because of movement of the shoulder girdle. They felt that, because of the mass of the trunk, small errors in trunk acceleration were capable of greatly influencing force and moment data. Fixing trunk length partially rectified this problem.

Certainly there was a problem in this study in achieving constant trunk length, not only because of movement of the shoulder girdle but also due to flexion at the hip. Even though the option for constant trunk length in the kinematic analysis program was invoked, it is unknown as to how much this corrected the problem. While Pezzack and Norman (1981) validated link segment modelling for up to six segments, using a seventh, as in the current study, was probably not a major problem.

BIOMECHANICAL PRINCIPLES

Using the criteria established in this study to evaluate the principle of summation of joint forces, Table 11 shows that the principle was fully supported for the propulsive phase of vertical and standing broad jumping. Thus, the extensor moments at all three leg joints produced net positive work for all subjects during the propulsive phase of both kinds of jumps.

The continuity principle, on the other hand, failed to gain full support in either type of jump when sequencing of the power contributions was used as the evaluating criterion (Table 11). However, partial support for continuity was in evidence as all subjects, in both standing broad and vertical jumping, showed hip-knee sequencing. Because of the criteria used in this study for determining support for both principles, it may be more appropriate to call them the principles of summation and continuity of joint powers instead of joint forces.

The utility of the two principles is presently questionable because of the difficulty in verifying whether the principles are being adhered to, because there is a lack of consensus as to how the summation and continuity principles should be interpreted and also because of the disagreement about what type of activities the principles apply to. The observational method of movement analysis promoted by Luttgens and Wells (1982), the National Coaching Certification Program (1979a, 1979b, 1981) and Norman (1975) does not provide information about the forces involved in a movement. It is erroneous to assume that the forces that cause movement of a body segment come from contractions of muscles inserting on the segment. Research by Ohman and Robertson (1981), Robertson (1982) and Robertson and Mosher (1985) have shown otherwise. Ohman and Robertson (1981) found that the elbow extensors did no work in achieving maximal hand velocity in a volleyball spike. Instead, concentric contraction of the shoulder extensors followed immediately by eccentric contraction of the shoulder flexors produced the desired action of the forearm and hand. Robertson (1982) and Robertson and Mosher (1985) discovered that for hurdling and soccer kicking, respectively, the knee extensors were not greatly involved in the extension of the lower leg. Rapid flexion of the thigh by the hip flexors followed by eccentric contraction of the hip extensors provided the major means by which the lower leg was extended.

Information about the forces involved in a movement can only be established through a kinetic analysis. However, the drawback to a kinetic analysis of the type done in this study is the substantial time delay between the performance and the availability of the information. This delay considerably reduces the usefulness of the information to the athlete or coach.

There is disagreement among authors about how these two principles apply to various types of activities. The

National Coaching Certification Program (1979a) says that the summation of joint forces principle applies to jumping, throwing, striking and kicking activities. In addition, the National Coaching Certification Program (1979b) also states that another principle, the summation of body segment velocities, is specific to throwing, striking and kicking skills. On the other hand, Norman (1975) and Dyson (1962) state that summation of joint forces and summation of forces, respectively, are primarily intended to deal with self-propulsion of the total body while a different principle, called either the summation of body segment speeds (Norman, 1975) or summation of throwing forces (Dyson, 1962), applies to movements where maximum hand, foot or implement speed is required. Other authors, using slightly different terms such as the summation of velocities (Kreighbaum and Barthels, 1981; Northrip et al., 1974) and the summation of segment velocities (Gowitzke and Milner, 1980), support the idea of a principle applicable only to throwing, kicking and striking actions.

With regard to the continuity principle, many authors feel that when the objective of a movement is to maximize the speed of the distal segment there is a definite sequencing of forces or body segment velocities (Broer and Zernicke, 1979; Bunn, 1972; Cooper and Glassow, 1976; Dyson, 1962; Gowitzke and Milner, 1980; Kreighbaum and Barthels, 1981; Luttgens and Wells, 1982; Morehouse and Cooper, 1950; National Coaching Certification Program, 1979a; Norman, 1975; Northrip *et al.*, 1974; Plagenhoef, 1971; Simonian, 1981). For jumping activities, however, where the objective is to move the athlete's total body mass, there is less agreement about whether sequencing occurs. The National Coaching Certification Program (1979a) says that the continuity principle holds for all types of power activities, implying that sequencing occurs in jumping movements. Dyson (1962) theorizes that to create maximum impulse during jumping all muscles involved should contract simultaneously. However, he believes that in practice, due to the nature of the construction of the human body, there is sequencing of muscular contractions from proximal to distal with all forces ending together. Therefore, the forces for jumping activities, according to Dyson (1962), would overlap one another. Broer and Zernicke (1979) feel that for heavy tasks, in which jumping presumably could be included, the forces are applied together.

An alternate view is expressed by Kreighbaum and Barthels (1981) who state that the degree of sequencing for movements is related to the purpose of the movement, the mass of the object to be moved and the strength of the athlete. Therefore, as the mass of the object to be moved increases, or the strength of the athlete decreases, or the desired accuracy of the movement outcome increases, or the force output requirement of the movement increases, the patterning of the activity changes from sequential to simultaneous segment involvement.

Summary. Before any attempt to validate the principles of summation and continuity can have meaning, precise definitions and criteria for evaluation need to be established. Only then will applying the principles provide useful information.

JOINT KINETICS

As a result of the similarity in the functions of the corresponding work phases (Table 10) for standing broad and vertical jumping, the hip, knee and ankle kinetics of the two sorts of jumps will be discussed together.

Hip Kinetics. Initially, the hip flexors were active concentrically (H1) to a small extent to lower the upper body. During approximately the last two-thirds of the contact time with the force plate the hip extensors were dominant. First they contracted eccentrically (H2) to stop lowering of the upper body and then they contracted concentrically (H3) to extend the upper body. H2 and H3 were episodes which dissipated and generated, respectively, the largest amounts of energy by any of the leg joints. From Figure 1 it can be seen that the hip is the only leg joint, for both types of jumps, that had a concentric contraction of the joint extensors (H3) that occurred before the start of the propulsive phase. The timing of H3 is such that the majority of the mass of the body is accelerating in an upward direction before the knee and ankle extensors contribute to the jumps.

The standing broad jump exhibited an extra work period (H4) which was very brief in duration. The hip flexors contracted eccentrically to slow upper body extension. The role of this work episode may have been to align the angle of the upper body, specifically the body center of gravity, with the angle of thrust of the legs. This would then leave gravity as the only force which would cause rotation of the body at toe-off.

Knee Kinetics. About the time H2 occurred the knee extensors contracted eccentrically (K1) to control both knee flexion and, indirectly, lowering of the upper body. Approximately one-third of the way into H3, the knee extensors came on concentrically (K2) to extend the knee. Immediately prior to toe-off, coincident with H4 in the standing broad jump, there was an eccentric contraction of the knee flexors (K3) of very short duration. The work dissipated during this episode was used to reduce the rate of knee extension which prevented the knee joint from hyperextending.

Ankle Kinetics. The first muscular activity consistent across all subjects at the ankle was a plantarflexion eccentric contraction (A1) which controlled the amount of ankle flexion during the countermovement. In the vertical jump this phase occurred at about the same time as H2 and K1 and for the standing broad jump the phase occurred about four-fifths of the way into H2 and three-fifths of the way into K1. A1 was followed by a strong concentric contraction of the plantarflexors (A2) as the ankle joint rapidly extended during the latter part of the propulsive phase. A2 occurred at around the same time as K2.

CONCLUSIONS

1. Over the entire jump there was a difference, favoring the vertical jump, in the extent to which muscles crossing the ankle joint contributed to the relative work done at the leg joints during standing broad and vertical jumping.
2. There was no difference in the extent to which muscles crossing the knee joint contributed to the relative work done at the leg joints during standing broad and vertical jumping for either the propulsive phase or the entire jump.
3. Over the entire jump for both standing broad and vertical jumping the knee musculature was not as important as the hip musculature in contributing to the work done at the leg joints.
4. During the propulsive phase of standing broad and vertical jumping, the hip extensors were more important than either the ankle plantar flexors or the knee extensors in generating work.
5. Using net work during the propulsive phase as the criterion, the principle of summation of muscle forces held for standing broad and vertical jumping.
6. The principle of continuity or sequencing of muscular contractions was not well supported for either standing broad or vertical jumping when the sequencing of joint power contributions was the evaluating criterion.

RECOMMENDATIONS

1. A reliability study is required to determine how consistent subjects are in achieving the same relative leg joint contributions during maximal jumping. This information is needed before researchers can be confident that a trend in joint contribution can be established for jumping activities.
2. The jumps, which were analyzed in the present study, should be subjected to another link segment analysis, incorporating a different link segment model, to determine whether the poor work-energy values were due to immeasurable work output or to an inappropriate link segment model.
3. Studies to establish the reliability of both force plates and associated computer programs are needed in order to provide investigators with an idea as to the accuracy of their results.
4. A next step in the application of joint power analysis of maximal jumping, would be its extension to sport related skills. The first type of activities to be analyzed should be movements that can be performed from a stationary position, such as blocking in volleyball and rebounding in basketball. Next would follow analysis of jumps off of one leg incorporating a run-up like a basketball layup and take-off for high, long and triple jumps. As well, joint power analysis should be

applied to the training activities utilized by athletes. This will provide information as to whether or not the requirements of the training activities closely match the joint work and power requirments of the sport skills.

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APPENDIX 1 - REVIEW OF LITERATURE

STANDING JUMPS

In 1921, Sargent (1921) presented a vertical jump test, eventually called the Sargent jump, which he thought took into account strength, speed, energy and dexterity. The scoring procedure that Sargent developed was an efficiency index that incorporated both the height and weight of the subject. A few years later, Sargent (1924) realized that the test measured power (the rate of work done) and not just the work done. He also found that height jumped was independent of the height and weight of a subject and therefore only the height jumped needed to be measured to evaluate performance.

In attempts to establish the test's usefulness, McCloy (1932) showed that the Sargent test results correlated with a composite score from a battery of track and field events that were thought to require power. Van Dalen (1940) determined that the test correlated with other vertical jump tests. They both concluded that the Sargent test was of some value in predicting an individual's potential ability in events requiring explosive muscular contractions.

Gray *et al*. (1962a) felt that many forms of the vertical jump could not be regarded as tests that measured only leg power because trunk extension and arm movements were allowed. They were also concerned that, although the Sargent test was supposed to be a test of power, the results were not expressed in units of power. With these thoughts in mind, they proposed a new version of the Sargent jump, termed the vertical power jump, which involved only the legs. They also provided a mathematical argument and equation for calculating the results in terms of force, time and distance, the components of power. However, the test was time-consuming because the weight and center of gravity of each subject along with two different height measurements had to be determined before the body power could be calculated. Gray _et al_. (1962b) eventually decided that it was simpler to put the results in terms of work done in a manner previously suggested by Sargent (1921).

Glencross (1966a) built a device he called the 'power lever' whose purpose was to measure the muscle power of specific joint actions in units of power. Using this device, he did correlation, multiple correlation and factor analyses on the jump and reach test, the standing broad jump, body weight plus four joint movements that he had determined from a previous study were important to vertical and standing broad jump performance (Glencross, 1966b). He concluded that while the vertical and standing broad jumps appeared to be indicators of leg power, they were limited as measures of muscle power. Despite their limitations, the standing broad jump and the vertical jump, in its varying forms, are still used for predicting athletic potential (Johnson and Nelson, 1974) and measuring physical fitness.

While there has been a large amount of research devoted to the standing jumps, especially the vertical jump, most of it has been limited to kinematic analyses of these jumps (Hay, 1975). The few kinetic studies that have been undertaken have concentrated almost exclusively on the vertical jump. Despite this fact the movement itself is still not well understood because investigations have largely focused upon using vertical jumping as a tool for examining features peripheral to the jump itself.

For example, some investigators (Asmussen and Bonde-Petersen, 1974; Bosco and Komi, 1979a, 1979b, 1980, 1981; Bosco et al., 1981, 1982a, 1982b, 1982c; Cavagna et al., 1971a; Fukashiro et al., 1983; Komi and Bosco, 1978a, 1978b; Viitasalo and Bosco, 1982) have used vertical jumping to analyze work augmentaion due to prestretching. In a few studies it was found that there was a significant difference in the rise of the height of the body center of gravity (c of g) in countermovement (CMJ) jumps (Asmussen and Bonde-Petersen, 1974; Bosco and Komi, 1979a; Komi and Bosco, 1978b) and drop (DJ) jumps (Asmussen and Bonde-Petersen, 1974; Komi and Bosco, 1978b) compared to jumps initiated from a squat or static (SJ) position, although there was no allowance taken for the lower starting position of the SJ. It was felt that the difference was attributable to the increased ability of a prestretched muscle to do positive work which occurred as a result of both the storage and release of energy by the muscle and muscle activation caused by the stretch reflex (Bosco and Komi, 1979b; Bosco et al., 1982b). Attempts to explain the additional work output of the body in countermovement and drop jumps have centered upon electromyographic (Bosco et al., 1982a, 1982b; Viitasalo and Bosco, 1982) and reflex potentiation (Bosco et al., 1982b) of various leg muscles, knee angle amplitude during jumping (Bosco and Komi, 1981; Bosco et al., 1981, 1982a, 1982c), the velocity of stretch of the knee extensors (Bosco and Komi, 1979b, 1981; Bosco et al., 1981, 1982b), fiber typing of the vastus lateralis muscle (Bosco and Komi, 1978a; Bosco et al., 1982c, 1983b; Komi and Bosco, 1979a; Viitasalo and Bosco, 1982) and the coupling time between the eccentric and concentric work phases of the knee extensors (Bosco et al., 1981, 1982b, 1982c).

Bosco et al. (1982a), using the vastus lateralis, vastus medialis and rectus femoris muscles, and Bosco et al. (1982b), omitting rectus femoris, found that the averaged integrated myoelectrical activity (IEMG) during both the eccentric and concentric phases of a CMJ (Bosco et al., 1982b) and continuous countermovement rebound jumping (Bosco et al., 1982a) were lower than the IEMG of the concentric phase of a SJ. From this they concluded that the greater work output during countermovement jumping was due to the utilization of energy stored in the muscles during the eccentric phase and not due to increased muscle activity. On the other hand, Viitasalo and Bosco (1982) found no difference in IEMG during either phase of a CMJ compared to a SJ, but their results included the myoelectrical activity of two additional muscles, namely gluteus maximus and gastrocnemius.

Two studies (Bosco et al., 1982b; Viitasalo and Bosco, 1982) also looked at IEMG for drop jumps and found that the IEMG during the eccentric phase of a DJ was greater than IEMG during a SJ, while for the concentric phase of DJ the opposite was true. These investigators felt that the increased neural activity during the eccentric phase of a DJ pointed out the possibility of increased muscle activitation due to spinal or cortical reflexes (Bosco et al., 1982b).

Bosco et al. (1982b) examined the ratio of IEMG to the average force during the eccentric and concentric work phases. For the eccentric phase the IEMG-force ratio was lower in the DJ than the CMJ, while for the concentric phase the ratio ascended from the DJ to the CMJ to the SJ. To these researchers this implied that the lower the IEMG-force ratio the greater the utilization of energy stored in the muscles during the eccentric phase because a smaller amount of EMG activity was needed per unit of force in both the eccentric and concentric phases.

Bosco et al. (1982a) looked at IEMG activity and knee amplitude in continuous countermovement rebound jumping. For small amplitude jumps, the IEMG was bigger during the eccentric phase and smaller during the concentric phase than the IEMG for the corresponding phases of the large amplitude jumps. In each type of jump the IEMG activity during both phases was smaller than the activity during the concentric phase of a SJ. Therefore, they concluded that for the same amount of IEMG activity during the concentric phase there was more positive work done in small knee amplitude jumps than in large amplitude jumps.

The parameters of velocity of stretch, coupling time and knee angle amplitude have interacted to influence performance in vertical jumping. Bosco and Komi (1981) showed that small amplitude movement at the knee joint enhanced the force and power output of the body when subjects performed vertical jumps with and without a countermovement. The same study showed a significant negative correlation between knee angle amplitude and knee joint angular velocity during prestretch, meaning that smaller amplitudes were associated with higher angular velocities. The knee joint angular velocity was assumed to reflect the velocity of stretch of the knee extensor muscles. In countermovement jumps, a significant positive correlation existed between length of coupling time, which was the transition period between the eccentric and concentric work phases where the knee angle remained constant, and knee movement amplitude (Bosco et al., 1981). It has been theorized that coupling time may be an important factor in the utilization of stored potential energy at the cross-bridge level of muscle tissue (Bosco et al., 1981, 1982c). Taken together, the various studies appear to indicate that to maximize the utilization of energy available because of prestretching, movements should be made with small amplitude preparatory actions to decrease coupling time and to increase the velocity of stretch of the involved muscles.

Performance in vertical jumping, as measured by power output (Bosco and Komi, 1979a; Bosco et al., 1983b), rise in height of body c of g (Bosco and Komi, 1979a; Komi and Bosco, 1978a; Viitasalo and Bosco, 1982) and percent use of energy stored during prestretch (Bosco et al., 1982c), has been correlated with muscle fiber composition of the vastus lateralis muscle, whose action was assumed to reflect the contribution of the leg extensors to the jump. For squat jumps (Bosco and Komi, 1979a) and during the first thirty seconds of continuous rebound jumping (Bosco et al., 1983b) the percent of fast twitch fibers correlated significantly in a positive manner with power output of the body. In countermovements jumps (Bosco et al., 1979a; Komi and Bosco, 1978a) and squat jumps (Bosco and Komi, 1979a) the percent of fast twitch fibers showed a significant positive relationship with the height of rise of the body c of g. The performance difference between DJ and CMJ as measured by the height of rise of the body c of g produced a significant positive correlation with percent of slow twitch fibers (Komi and Bosco, 1978a). Viitasalo and Bosco (1982) divided their subjects into 'slow' and 'fast' groups according to the percent of fast twitch fibers. They found a significant performance difference in favor of the 'fast' group in the height of rise of the body c of g while performing a SJ and a significant difference favoring the 'slow' group when performance differences between DJ and CMJ were compared.

Komi and Bosco (1978b) attempted to measure the percent utilization of elastic energy during a CMJ and DJ. They compared the maximum kinetic energy level during the eccentric phase of jumping to the change in maximum kinetic energy between a CMJ and a SJ and between a DJ and a SJ during the concentric phase. Their findings were that the percent utilization of elastic energy was greater in a CMJ than a DJ and that females when compared to males used a greater portion of the available elastic energy in both the CMJ and DJ conditions.

Many researchers have used vertical jumping to examine the power output of the human body during a basic movement (Bosco and Komi, 1979a, 1979b, 1980, 1981; Bosco _et al_., 1981, 1982b, 1983a, 1983b, 1983c; Cavagna _et al_., 1971a; Davies, 1971; Davies and Rennie, 1968; Desiprés, 1976). Vertical jumping has also been employed in studies comparing the values for take-off velocity of the body c of g found by force platform and cinematographic techniques (Komi and Bosco, 1978b; Lamb and Stothart, 1978; Luhtanen and Komi, 1978b).

Hay _et al_. (1976, 1978, 1981) attempted to develop a model for identifying factors that limit performance in specific tasks while Komor _et al_. (1981) used a control systems analysis to study technique optimization. In both cases the vertical jump was the movement chosen for analysis.

Hunebelle and Damoiseau (1973) examined the force-time (impulse) curve of subjects performing vertical jumps on a force plate and noticed that poorer jumpers produced curves that were triangular in shape and that they took a longer time to jump than the better jumpers, who were characterized by trapezoidal shaped curves. Tveit (1976) looking at the horizontal forces and horizontal impulses in vertical jumping showed that both were smaller in jumps performed with a preparatory countermovement than without.

In an attempt to provide specific information about what factors contribute to vertical jump performance, researchers have used several approaches. The segmental approach (Luhtanen and Komi, 1978b; Miller and East, 1976) found that the segmental contribution to the impulse generated and to the total linear momentum developed was influenced by the mass of the body segments. Luhtanen and Komi (1978b) also looked at the specific contributions of various joint actions to take-off velocity and determined that 56 percent of take-off velocity was caused by knee extension, 22 percent by plantar flexion, 10 percent by trunk extension, 10 percent by arm swing and 2 percent by head swing.

The joint moment technique (Hay et al., 1978, 1981) found that some joint moments during particular time intervals of the jump correlated significantly with jump performance. A problem with this technique, as pointed out by Hubley and Wells (1983), is that it does not differentiate between joints undergoing isometric contraction, and therefore not contributing toward height jumped, and those joints actively involved in jump performance.

Both Bangerter (1968) and Berger (1963) examined the effects of strength training programs on vertical jump performance. Bangerter (1968), using isolated joint exercises, concluded that the hip and knee extensors were important in vertical jumping but not so for the ankle plantar flexors. In the study by Berger (1963), subjects either trained dynamically by doing one of squats, jump squats and vertical jumps or isometrically at two different positions of knee flexion. He found that the groups that trained by doing squats and jump squats improved significantly more in vertical jump performance than the groups that trained isometrically or by simply jumping.

A study by Roy et al. (1973) examined some kinematic and kinetic features of the standing broad jump as performed by groups of boys aged 7, 10, 13 and 16 years. They observed that the maximum horizontal and resultant velocities at take-off increased with age while maximum vertical velocity was basically the same across age groups. They also noticed that both the maximum vertical acceleration and the angle of take-off were similar for all age groups. Due to the fairly consistent results in several measures for all age groups they concluded that the basic neuromuscular patterns for the standing broad jump were well established by 7 years of age.

While the standing broad jump has also been used as an activity to validate link segment modelling of a human (Pezzack and Norman, 1981), to date, the standing broad jump has not been investigated as extensively as the standing vertical jump.

WORK AND POWER IN HUMAN LOCOMOTION

Since the classic works of Fenn (1930a, 1930b) and Elftman (1939a, 1939b) both work and power have been used as measures to quantify physical activity. Much research has focused upon the mechanical energy and power aspects of the total body during walking (Cappozzo *et al.*, 1976; Cavagna, 1975; Cavagna and Kaneko, 1977; Cavagna and Margaria, 1966; Cavagna *et al.*, 1963, 1976; Fenn, 1930a, 1930b; Gersten *et al.*, 1969; Luhtanen and Komi, 1980; Pierrynowski *et al.*, 1980; Ralston and Lukin, 1969; Winter *et al.*, 1976a; Zarrugh, 1981a), running (Cavagna, 1975; Cavagna and Kaneko, 1977; Cavagna *et al.*, 1964, 1971b; Fukunaga *et al.*, 1978; Luhtanen and Komi, 1978a, 1980; Williams and Cavanagh, 1983) and jumping (Bosco and Komi, 1979a, 1979b, 1980, 1981; Bosco *et al.*, 1981, 1982b, 1983a, 1983b, 1983c; Cavagna *et al.*, 1971a; Davies, 1971; Davies and Rennie, 1968; Desiprés, 1976; Luhtanen and Komi, 1980). However, considerably less research has centered upon joint and muscle energetics.

Elftman (1939a, 1939b), while looking at walking, was the first to combine joint reaction forces and net joint moments with segmental and joint kinematics to calculate the rate of change of energy for the leg segments, the rate of energy transfer through the leg joints due to joint forces (joint force power) and the rate of work done by muscles crossing the joints (muscle power). He later extended this work to running (Elftman, 1940). Since then the work on joint energetics has focused on two complementary types of analysis.

A segmental power analysis has been used to analyze the energy and power changes in lower limb segments during running (Chapman and Caldwell, 1983) and walking (Quanbury et al., 1975; Robertson and Winter, 1980; Winter and Robertson, 1978; Winter et al., 1976b). This type of analysis provides information about where energy generated by muscles crossing a joint goes, where energy absorbed at a joint comes from and where energy transferred through a joint between segments goes. When a segmental power analysis is combined with a segmental energy analysis, a work-energy comparison can be made to check the accuracy and validity of the analysis techniques (Quanbury et al., 1975; Robertson and Winter, 1980; Winter et al., 1976b).

A joint power analysis allows the work done by muscles crossing a joint to be calculated, which then enables the role and importance of the muscles in an activity to be determined. This type of analysis has been used to examine the contribution of the muscles crossing the leg joints in walking (Bresler and Berry, 1951; Cappozzo et al., 1976; Morrison, 1970; Zarrugh, 1981b), race walking (White and Winter, 1985), jogging (Winter, 1983), running (Robertson, 1985), jumping (Hubley and Wells, 1983; Robertson and Fleming, 1986) and soccer kicking (Robertson and Mosher, 1985).

Bresler and Berry (1951), Cappozzo et al. (1976) and Zarrugh (1981b), looking at walking, and White and Winter (1985), examining race walking, found that for one stride of each activity the muscles crossing the ankle and hip joints generated more energy than they received while the opposite was true for the muscles of the knee joint. While the overall trend for energy generation and absorption at the various leg joints was similar in both walking and race walking, the specific patterning of energy contribution was quite different. In walking, the ankle and hip joints together provided the majority of the power required by the body during the stance phase (Cappozzo et al., 1976; Zarrugh, 1981b) but for race walking the main contributor to forward propulsion during the stance phase was the ankle joint with the hip joint contributing to forward motion only somewhat during late stance phase but mainly during early swing phase. In both forms of locomotion, the knee joint had periods of energy absorption prior to toe-off and heel-contact (Cappozzo et al., 1976; White and Winter, 1985; Zarrugh, 1981b).

For one stride of jogging (Winter, 1983) and during the stance phase of running (Robertson, 1985) it was discovered that the roles of the muscles crossing the knee and ankle joints were similar to their roles in walking and race walking, but the role of the hip joint was very different. During the stance phase of running the muscles of the hip joint were net absorbers of energy while no conclusive role was evident at the hip for one stride of jogging.

Hubley and Wells (1983), using the work-energy approach, attempted to quantify the amount of positive work contributed by the muscles crossing the hip, knee and ankle joints during vertical jumping. They found that for the propulsive phase of a CMJ the hip, knee and ankle muscles contributed 27.5, 49.0 and 23.5 percent, respectively, to the work done by the legs. For jumps initiated from a squat position the joint contributions were almost identical to those in countermovement jumping.

Work done by Robertson and Fleming (1986) examined the propulsive phase of both vertical and standing broad jumping. They found that for vertical jumping the muscles crossing the hip, knee and ankle joints were responsible, respectively, for 40.0, 24.2 and 35.8 percent of the total work done at the leg joints. In standing broad jumping the respective contributions of the hip, knee and ankle musculatures were 45.9, 3.9 and 50.2 percent. These results indicated that the muscles crossing the knee joint were not as important in contributing to the net work done during jumping as the muscles of the ankle and hip joints. Furthermore they showed that the muscles of the legs contributed differentially to the two types of jumps.

The studies on joint power indicate that for movements primarily concerned with horizontal displacement of the body the knee joint was a net absorber of energy. They also indicate that the role of the muscles crossing the hip joint was different in double leg support activities, such as walking, race walking and standing broad jumping, than in single leg support movements like jogging and running. In double leg support activities the muscles of the hip joint were important in contributing to forward motion but that was not the case in single leg support movements.

BIOMECHANICAL PRINCIPLES

To make biomechanical information more easily understood and applicable, the information is sometimes summarized into a principle. Two examples of this are the biomechanical principles of summation of joint forces and continuity of joint forces.

Simply stated, the principle of summation of joint forces says that to produce the fastest, most powerful movement possible, all the joints that can contribute to the movement must be used and used to their fullest extent. This principle has been described by Broer and Zernicke (1979), Bunn (1972), Cooper and Glassow (1976), Luttgens and Wells (1982), Morehouse and Cooper (1950), Norman (1975) and the Level I Coaching Theory manual of the National Coaching

Certification Program (1979a). Other authors, when discussing summation of forces, interpret the principle as referring to the sequencing and timing of internal forces contributing to a movement (Broer and Zernicke, 1979; Bunn, 1972; Cooper and Glassow, 1976; Dyson, 1962; Jensen and Schultz, 1977; Northrip *et al*., 1974; Plagenhoef, 1971; Simonian, 1981).

The sequencing of muscular contractions for a movement is explained by the principle of continuity of joint forces which states that the order of the muscle groups or segments used should be from the largest to the smallest (Bunn, 1972; Kreighbaum and Barthels, 1981; National Coaching Certification Program, 1979a; Norman, 1975; Simonian, 1981), from the strongest to the weakest (Bunn, 1972; Dyson, 1962; Simonian, 1981), from the proximal to the distal (Broer and Zernicke, 1979; Dyson, 1962; Gowitzke and Milner, 1980; Luttgens and Wells, 1982; National Coaching Cerfification Program, 1979a; Norman, 1975; Plagenhoef, 1971), from the slowest to the fastest (Dyson, 1962; Luttgens and Wells, 1982; Simonian, 1981) or from the heaviest to the lightest (Dyson, 1962; Gowitzke and Milner, 1980; Kreighbaum and Barthels, 1981; Luttgens and Wells, 1982; Morehouse and Cooper, 1950).

There is some discrepancy among authors as to how the above two principles apply to various types of activities. The National Coaching Ceritification Program (1979a) says that the summation of joint forces principle applies to jumping, throwing, striking and kicking activities. In addition, the National Coaching Certification Program (1979b) also states that another principle, the summation of body segment velocities, is applicable only to throwing, striking and kicking skills. On the other hand, Norman (1975) states that summation of joint forces is primarily intended to deal with self-propulsion of the body while a different principle, the summation of body segment speeds, applies to movements where maximum hand, foot or implement speed is required. Dyson (1962) concurs with this opinion when he mentions that summation of forces is particularly important in jumping while summation of throwing forces is applicable to throwing movements. Other authors using slightly different terms, the summation of velocities (Kreighbaum and Barthels, 1981; Northrip et al., 1974) and the summation of segment velocities (Gowitzke and Milner, 1980), support the idea of a principle specific to throwing, kicking and striking actions.

Concerning the continuity principle, the majority opinion is that for throwing, kicking and striking activities, where the objective is to maximize the speed of the distal segment involved in the movement, there is a definite sequencing of forces or body segment velocities (Broer and Zernicke, 1979; Bunn, 1972; Cooper and Glassow, 1976; Dyson, 1962; Gowitzke and Milner, 1980; Kreighbaum and Barthels, 1981; Luttgens and Wells, 1982; Morehouse and Cooper, 1950; National Coaching Certification Program, 1979a; Norman, 1975; Northrip et al., 1974; Plagenhoef, 1971; Simonian, 1981). The sequencing of forces occurs in such a manner that each successive force is applied when the preceding force has made its maximum contribution toward increasing the velocity of the more distal segment or segments (Broer and Zernicke, 1979; Bunn, 1972; Cooper and Glassow, 1976; Morehouse and Cooper, 1950; Plagenhoef, 1971; Simonian, 1981).

For jumping activities, however, where the objective is to move the athlete's total body mass, there is less agreement about whether sequencing occurs. Again the National Coaching Certification Program (1979a) says that the continuity principle holds for jumping as well as for throwing, striking and kicking activities. This implies that sequencing occurs in jumping movements. Dyson (1962) theorizes that to create maximum impulse during jumping all muscles involved should contract simultaneously. However, he says that in practice, due to the nature of the construction of the human body where the stronger body parts are also the heaviest and thus have the greatest inertia, there is sequencing of muscular contractions from proximal to distal with forces ending together. Therefore, the forces for jumping activities, according to Dyson (1962), would overlap one another as opposed to throwing, kicking and striking movements where the forces would be generated successively. Other investigators are of the opinion that the forces are applied simultaneously. Broer and Zernicke

(1979) believe this to be the case in heavy tasks, in which jumping presumably could be included, while for the vertical jump, Morehouse and Cooper (1950) state that the two joint muscles of the thigh acting at both the knee and hip joints cause the knees and hips to extend simultaneously.

An alternate view is expressed by Kreighbaum and Barthels (1981) who state that the degree of sequencing for movements is related to the purpose of the movement, the mass of the object to be moved and the strength of the athlete. They envision a continuum. At one end are movements whose primary objective is the development of high speed. This is achieved through sequential movement of body segments. At the other end of the continuum are movements whose primary emphasis is on force generation or accuracy. This is accomplished through the simultaneous movement of body segments. Therefore, as the mass of the object to be moved increases, or the strength of the athlete decreases, or the desired accuracy of the movement outcome increases, or the force ouput requirement of the movement increases, the patterning of the activity changes from sequential to simultaneous segment involvement.

Two other investigators have put forth principles which are applicable to jumping. The principle of superposition of angular speeds in joints (Koniar, 1973) says that the optimal performance by an athlete will occur when the angular velocities of the joints involved in a movement peak simultaneously. Koniar (1973) found that for a vertical jump, the best performance occurred when the maximum hip, knee and ankle angular velocities were achieved at the same time.

Hochmuth and Marhold (1978) gave a theoretical explanation of the principle of the optimal position of the force maximum. By observing athletic performances they discovered that humans can develop maximum acceleration for only a short period of time. From a theoretical analysis of acceleration-time dynamics they concluded that the positioning of the maximum force depends upon the aim of the activity. Given the constraint that an object must move a set distance, then to cover that distance in a minimum of time the maximum force must occur at the beginning of the movement. If the aim is to impart maximum velocity to the object, such as in jumping, the maximum force must occur at the end of the acceleration phase.

Recently there have been several studies which have endeavoured to establish the usefulness of various principles in different activities. Robertson and Fleming (1983) looked at the applicability of the principles of summation and continuity of joint forces to the vertical jump and standing broad jump. From the results of a joint power analysis for the legs they concluded that the summation principle held for the vertical jump but not the standing broad jump because in the broad jump the muscles crossing the knee joint were net absorbers of energy. They also concluded that the continuity principle did not hold for either jump as all three extensor muscle groups of the legs contracted nearly simultaneously instead of sequentially as expected.

Three studies have looked specifically at the principle of summation of segmental velocities. For the studies to support the principle, the researchers needed to find an acceleration-deceleration sequence at all the joints involved in the motion except the most distal one. The acceleration-deceleration sequence at a joint was to be exhibited by a concentric contraction of the agonist muscles across the joint followed by an eccentric contraction of the antagonist muscles (Jöris et al., 1985; Robertson and Mosher, 1985). This sequencing of muscular contractions was assumed to help accelerate, in a whip-like fashion, the segments distal to the joint. Both Ohman and Robertson (1981) and Robertson and Mosher (1985) in their studies concluded that this principle did not completely hold. Ohman and Robertson (1981) showed that the elbow joint did not exhibit an acceleration-deceleration sequence and that in fact the elbow extensors did no work in achieving maximal hand velocity in a volleyball spike. Instead, concentric contraction of the shoulder extensors followed immediately by eccentric contraction of the shoulder flexors produced the desired action of the forearm and hand. Robertson and Mosher (1985) found that for soccer kicking practically no work was done by the knee extensors to extend the lower leg. Again, the expected acceleration-deceleration sequence was not evident at the knee joint. The third study, by Jöris et al. (1985), found support for the principle and concluded that development of high segmental velocities in the overarm throw by female handball players was a prerequisite for achieving fast ball velocity. They based their conclusion not on a segmental analysis and not on an acceleration-deceleration patterning analysis of the involved joints but on the finding that the maximum linear velocities for the hip, elbow, wrist and ball all occurred and increased sequentially, from proximal to distal.

Another study by Robertson (1982), while not looking specifically at the usefulness of the summation of segmental velocities principle, found that the knee extensors were not involved in the extension of the lower leg in hurdling. Here, similar to the soccer study, rapid flexion of the thigh by the hip flexors followed by eccentric contraction of the hip extensors provided the means by which the lower leg was extended. This study would also not fully support the summation of segmental velocities principle due to the lack of an acceleration-deceleration sequence at the knee joint.

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