
Timing in Vertical Jumps

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INTRODUCTION

The height achieved in a vertical jump for maximum height is dependent on the external work done to increase the kinetic energy of vertical translation of the centre of gravity (CG). In turn this work is dependent on the vertical component of the ground reaction forces and the displacement through which the CG is accelerated by these forces during the period of ground contact. Stretching of the elastic components, primarily the Achilles' tendon (Alexander and Bennet-Clark, 1977; van Ingen Schenau, 1984; Bobbert, **Huijing**, and van Ingen Schenau, 1986a; 1986b), can result in increased ('potentiated') vertical force magnitudes (Cavagna, Sabiene, and Margaria, 1965; **Asmussen** and Bonde-Petersen, 1974; Komi and Bosco, 1978; Bosco and Komi, 1979; Bosco, Komi, and **Ito**, 1981). This prestretching of the elastic elements may be accomplished by a downward counter movement prior to the upward movement of the jump. Several researchers have studied the effect of elastic energy by comparing jumps performed with a counter movements (**CMJs** with jumps from a static starting position (**SJs**) and have suggested that the utilisation of stored elastic energy becomes less important at larger amplitudes of knee flexion (Bosco and Komi, 1981; Bosco, Komi, and **Ito**, 1981; Bosco et al, 1982). This was thought to be due to the longer time period of the jump and the associated dissipation of elastic energy. Modeling of muscle has shown that optimal timing of forces is related to the longer time period of the jump and the associated dissipation of elastic energy. Modeling of muscle has shown that optimal timing of forces is related to the interaction of the elastic and contractile elements of the elastic and contractile elements of the system (Denoth, 1983; Bobbert, **Huijing**, and van Ingen Schenau, 1986a; 1986b).

These findings are pertinent with respect to the timing of forces to **optimise** performance. It is also important that large forces are achieved during the time when the displacement is changing rapidly, that is, during the period of large upward velocity late in the contact period of the jump (Hochmuth and **Marhold**, 1978). This 'pattern' of forces results in great external power output and, as a consequence, a large kinetic energy of the CG. In jumps involving large amplitudes of knee flexion the large forces produced by the prestretch may not occur with appropriate timing to produce a high work output. That is, the potentiated forces may occur before the time when the vertical displacement is changing rapidly. Further, it is likely that in **SJs** stretching of the elastic elements occurs early in the jump through the work of the contractile elements and that some of this stored energy contributes to external work late in the jump.

Thus, broadly speaking two aspects of timing of a movement to enhance performance have been identified. The first is that the pattern of innervation results in a summation of the force contributions of the contractile and elastic components of the muscle to produce an increase in total force output. The second is that the pattern of these forces is such that a large external power output, and therefore great external work, results. A simple means of investigating the timing aspect is to compare the work output for a particular pattern of vertical ground reaction forces to a theoretical maximum (TM). In jumping the TM force pattern is that which **maximises** the vertical fraction of the kinetic energy of translation of the CG within the available range of displacement. This pattern is one in which the force level is sustained throughout the upward movement phase.

Whereas considerable research has investigated enhancement of work output which results from the force potential gained from the prestretch, little consideration has been given to the pattern of the ground reaction forces. Also, there have been few studies which compare **CMJs** and **SJs** when the jumpers are free to select their own movement amplitudes. We contend that to permit natural or optimal timing in jumping tasks the subjects should be free to select their own movement amplitudes. Constraining subjects to preset amplitudes may prevent them from achieving the desired summation of the force contributions of the elastic and contractile elements at the appropriate time.

The purpose of this study was to compare the energy output of **CMJs** and **SJs** and the differences in the pattern of forces and force potentiation of **SJs** with respect to the **CMJs** when subjects were free to choose their own movement amplitudes.

METHOD

SUBJECTS: This paper presents the findings of two related experiments. In the **first**, data was collected from 3 male and 2 female subjects (**S1** to **S5**). In the second 8 male and 4 female subjects were tested (**S6** to **S17**). Subjects **S1** to **S5** performed an 8 trial block of **CMJs** and an 8 trial block of **SJs** with the block order **randomised** across subjects. Subsequently, the best 6 trials of each jump type (in terms of the **final** overtrade velocity) were included in the analysis. Subjects **S6** to **S17** were each required to do 5 **CMJs** and 5 **SJs** and all of these were subsequently included in the analysis. For the **CMJ** condition the subject commenced in an upright and stationary position then, in a continuous movement, crouched and jumped vertically upwards. For the **SJ** condition the subject commenced from a **comfortable** and stationary crouch position of their choice, that is, with no constraint on the angle of knee flexion used for the jumps. If any counter movement was evident from the force-time record the jump was repeated. For most subjects several trials of **SJs** were administered before the subject learned to jump without any unweighting. Rest periods of 30 seconds were provided between jumps to reduce possible effects of fatigue on performance.

DATA COLLECTION: The vertical component of the ground reaction force was recorded by means of a force platform (Kistler, model 9281b), sampled at **500Hz**, and stored in a Magnum personal computer. All kinematic and kinetic measures in this study are based on the vertical component of the ground reaction force. All subsequent references to these variables refer only to the vertical component.

DATA ANALYSIS: Acceleration of the CG was regarded as the ground reaction force divided by subject mass. From this acceleration the change in velocity and change in displacement were integrated. The positive phase was defined as the period from the instant of the minimum displacement (identified from the displacement-time function) to the instant that the ground reaction force fell to body weight. The fraction of power which produces a change in the vertical fraction of kinetic energy of translation, normalized for mass, was determined as the product of acceleration and velocity of the CG. This was expressed as a function of time and integrated over the period of the positive phase. This value at the end of the positive phase represented the kinetic energy due to vertical translation of the CG possessed at the end of the positive phase (**KE**).

For every jump performed a **TM** was calculated. This was based on a constant CG acceleration equivalent to the peak acceleration produced during the actual jump. The final velocity is maximised when the subject

maintains this peak acceleration throughout the entire positive phase. Because the jumper is constrained by the available range of extension, that is, the height to which the CG can be raised at takeoff with respect to the starting height, the duration of the positive phase of the TM was limited by this constraint. This period was obtained from the formula: $d = ut + (1/2)at^2$. Since the initial velocity u is zero by definition of the positive phase and the displacement d is the vertical displacement of the CG utilized in the actual jump, t is given as: $t = (2d/a)$ where a is the constant acceleration equal to the peak acceleration attained during the positive phase of the actual jump. Velocity, displacement, power, and external work of the optimal jump were then calculated as functions of time and time normalised to percentiles of the positive phase.

CONTRIBUTIONS TO THE DIFFERENCE IN KINETIC ENERGY IN CMJ AND SJ: In this study it was of interest to relate the pattern of applied forces and the potentiation of force to the performance differences between the CMJ and SJ. The CMJ was used as the reference and the improvement or decrement in work of the SJ with respect to the CMJ was attributed to three separate contributions. These were the contribution due to the pattern of forces (ΔKE_p), the difference due to the range of displacement utilised (ΔKE_d) and the difference due to force potentiation (ΔKE_{pot}). To calculate the ΔKE_p contribution the KE of the CMJ was normalised to the same TM as the SJ. Thus, the effect of the difference in force magnitudes was removed enabling direct comparison of the jumps in terms of the force pattern. The KE_p contribution was the difference of the actual KE of the SJ and the normalised CMJ given by:

$$\Delta KE_p = KE_{sja} - (KE_{cja} * KE_{sjtm} / KE_{cjm})$$

Where ΔKE_p is the difference in energies attributed to the temporal pattern of the two jumps and the subscripts sja , $sjtm$, cja , and cjm refer to the actual and TM SJs and CMJs respectively.

Similarly, since a force acting over a greater distance does more work than an equivalent force over a shorter distance, the discrepancy in distance between the CMJ and SJ had to be taken into account. The difference in KE due to this discrepancy was determined by:

$$\Delta KE_d = (KE_{cja} * d_{sj}/d_{cmj}) - KE_{cja}$$

Where ΔKE_d is the difference in kinetic energies of the CMJ and SJ attributable to the discrepancy in movement paths (vertical displacements) of the two jumps and d_{sj} and d_{cmj} are the vertical displacements of the CG utilised in the SJ and CMJ respectively. It was anticipated that the range of displacement utilised in the SJs would be larger than that of the CMJs to compensate for the inability to store energy by means of the counter

movement.

The remainder of the difference in KE between the CMJs and SJs is attributable to the difference in force potential (ΔKE_{pot}), that is, the difference in KE due to difference in the overall magnitudes of the forces through the upward movement.

$$\Delta KE_{pot} = KE_{sja} - KE_{cja} - \Delta KE_p - \Delta KE_d$$

RESULTS AND DISCUSSION

All subjects except S2 and S15 displayed shorter durations of the positive phase for the CMJs than the SJs. This is reflected in the respective group means (CMJ = 271ms; SJ = 387ms), which are significantly different ($p < 0.01$). Two male subjects (S3 and S5) closely approached the duration of the TM in the CMJ indicated by mean temporal differences of only 6 and 11ms respectively. With the exception of S15 the times of the actual CMJs approached the time of their respective TMs much more than the SJs approached their respective TMs. Taken over all 17 subjects the mean time difference between the actual and TM jumps was significantly smaller ($p < 0.01$) for the CMJs (46ms) than did the SJs (149ms). These results indicate that in terms of the duration of the jump the force patterns of the CMJs approached those of the TMs far more closely than the force patterns of the SJs approached those of their TMs. There was no significant difference between the mean duration of the TMs of the CMJs (226ms) and the TMs of the SJs (238ms).

EXTERNAL WORK PERFORMED DURING THE POSITIVE PHASE: The mean work performed in the SJs ($3.86J \cdot kg^{-1}$) was only slightly less than that of the CMJs ($4.05J \cdot kg^{-1}$) and this difference was not significant at the 0.05 level ($p = 0.21$). In terms of the additional height achieved after takeoff this represents a mean difference of approximately 0.02m. Despite the lack of a counter movement 10 of the 17 subjects performed equivalent (Ss 2, 3, 5, 9, 11, 13) or greater work (Ss 4, 6, 10, 17) in the SJs than in the CMJs. This strongly suggests that for many subjects there is no gain in ability to generate height by using a counter movement providing the jumper is free to choose the range of displacement. There was a tendency for the jumpers to approach the TMs in the CMJs more than in the SJs. The group mean KE of the CMJs was 75.8% of the TMs while that of the SJs was 72.6% of the TMs. There was a smaller difference in KE between the actual and TMs for the CMJs ($1.30J \cdot kg^{-1}$) than the SJs ($1.48J \cdot kg^{-1}$). A correlated T test showed that there was a significant difference between the CMJs and SJs in both of these measures ($p < 0.02$).

However S3, S4 and S6 had a higher percentage of the TM in the SJs than the CMJs, indicating a superior pattern of forces in the SJs than the CMJs. This implies that the forces were sustained at a level close to the peak during the period in which the bulk of the work was being performed. Figures 1a and 1b display the mean external work (for the subjects involved in the first experiment: S1 to S5) for the actual and TMs of the CMJs and SJs respectively expressed as functions of mean time with respect to the end of the positive phase. Clearly, the bulk of the additional work performed in the TMs occurred during the last 50ms of the positive phase coinciding with the rapid decline in accelerations of the actual CMJs and SJs at this time. Peak forces were achieved at a time when velocities of the CG are quite high (mean = $2.0\text{m}\cdot\text{s}^{-1}$). In view of this fact the body appears well suited to achieving high power outputs by maintaining high forces late in the positive phase. However, it becomes impossible to sustain these forces during the last 50ms of the positive phase. Based on the comparison of the work outputs of the actual and TMs the inability to maintain high forces close to full extension is the biggest limitation to performance. Effective release of energy stored in the Achilles' tendon could be expected to enhance power output late in the jump providing this energy had not been dissipated previously without contributing to external work.

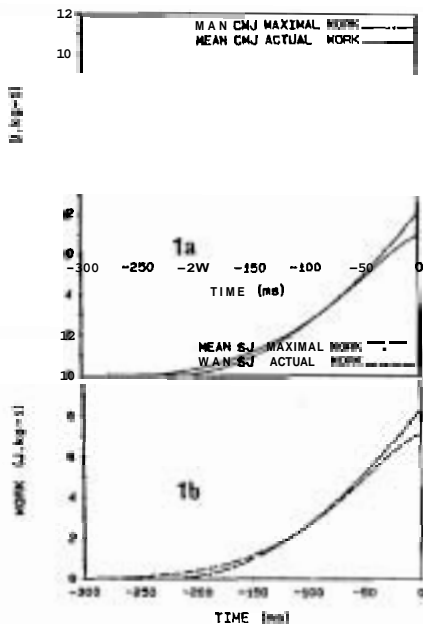


Figure 1: The mean (of all trials of S1 to S5) actual and theoretically maximal external work (vertical component of CG kinetic energy) as a function of mean time of the CMJs (a); and SJs (b)

Figure 2 shows that there are small differences between the CMJs and SJs in the power as a function of time from the end of the positive phase. The major difference is that it takes longer to develop power in the SJs than in the CMJs. The similarity of the power profiles of the CMJs and SJs despite the dissimilarity of the acceleration profiles arises from the fact that the bulk of the power output occurs late in the positive phase when the CG velocity is high. By this time the forces are high in both jump types.

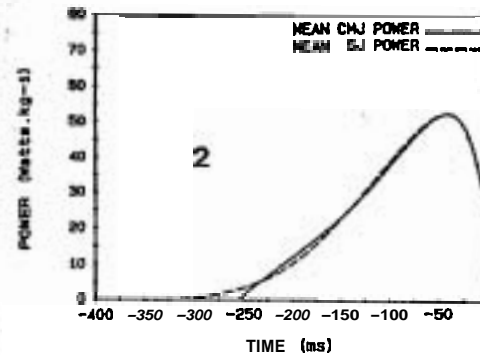


Figure 2: Illustrates the mean (mean of all trials of S1 to S5) external power of the CMJs and SJs as functions of mean time

CONTRIBUTIONS TO THE DIFFERENCE IN WORK. Table 1 shows the contributions to the difference in external work of the SJs with respect to the CMJs. It is evident that there is great variability among subjects with respect to the source of the ΔKE of the two jumps. However, it is evident that ΔKE_d and ΔKE_{pot} have a greater influence on AKE than ΔKE_p . This is reflected in the correlations of these variables with AKE (ΔKE_d , $r = .45$; ΔKE_{pot} , $r = .203$; ΔKE_p , $r = .089$). There was a negative association between the ΔKE_d , and ΔKE_{pot} ($r = -0.72$). This supports the idea that the higher accelerations and power associated with shorter displacements are the result of the use of stored elastic energy and is consistent with the findings of Bosco et al, 1981; 1982a, and Bosco and Komi, 1981. There were 4 subjects who performed substantially more work in the SJs than the CMJs (Ss 4, 6, 10, 17). In all 4 cases a greater range of displacement was utilised in the SJs than in the CMJs. However, in the case of S4 the bulk of the difference ($0.28\text{J}\cdot\text{kg}^{-1}$) was due to the potentiation of forces in the static jump rather than to the increased displacement. The fact that for 7 subjects (Ss 2, 4, 5, 9, 11, 15, and 17) showed a higher level of force potential was achieved in the SJs than the CMJs implies that elastic energy may also be

utilised in the SJs. In this case, rather than the energy being stored as a result of a counter movement, the strain energy in the tendons was developed by muscular activity during the positive phase and was released during plantar flexion late in the positive phase. This possibility is further supported by the fact that Ss 2, 5, 9, and 11 were able to achieve equivalent final work in the SJs compared to the CMJs and that S4 actually achieved greater final work in the SJs than the CMJs. For these subjects it appears that elastic energy is utilised at least as effectively in the SJs as in the CMJs and that the counter movement is of little benefit. Other subjects to perform better in the SJs than CMJs were Ss 6, 10, and 13. Although their contribution due to potentiation was slightly less for the SJs than the CMJs their overall work was greater due to the use of a greater displacement.

TABLE 1
KINETIC ENERGY AND CONTRIBUTIONS TO THE DIFFERENCE
IN KINETIC ENERGY ($\text{J}\cdot\text{kg}^{-1}$)

S	KE_{CMJ}	KE_{SJ}	ΔKE	ΔKE_p	ΔKE_d	$\Delta\text{KE}_{\text{pot}}$
1	3.69	2.99	-0.70	-0.18	0.37	-0.89
2	3.21	3.17	-0.04	0.02	-0.39	0.33
3	4.00	3.96	-0.04	0.14	1.53	-1.71
4	3.42	3.86	0.44	0.05	0.11	0.28
5	4.08	4.12	0.04	-0.32	-0.74	1.10
6	4.93	5.26	0.33	0.17	0.45	-0.29
7	3.91	3.57	-0.34	-0.80	1.30	-0.85
8	4.31	3.83	-0.48	-0.03	-0.19	-0.64
9	3.36	3.30	-0.07	-0.21	0.03	0.11
10	3.52	3.80	0.27	-0.12	0.50	-0.10
11	3.82	3.84	0.02	-0.08	-0.18	0.29
12	4.71	2.56	-2.14	-0.11	-1.87	-0.17
13	3.59	3.69	0.10	-0.14	0.34	-0.11
14	3.53	3.09	-0.45	-0.16	0.56	-0.85
15	4.84	4.45	-0.39	-0.00	-0.54	0.15
16	5.33	5.15	-0.18	-1.21	2.38	-1.36
17	4.65	5.01	0.36	-0.18	0.50	0.05

As expected from the work expressed as a percentage of the TMs in the previous section, the SJs generally had a slightly inferior pattern. This was reflected in the contribution of ΔKE_p to the difference in kinetic energy of the SJs and CMJs. However, based on the magnitudes of these negative contributions this variable was not the major factor contributing to the difference between CMJs and SJs.

SUMMARY AND CONCLUSION

CMJs and SJs were compared to investigate differences with respect to two aspects which influence the development of kinetic energy of vertical translation of the CG. These were the tendency to sustain forces at their peak level throughout the upward movement (termed the 'pattern' of forces), and the contribution to KE due to achieving large forces over the period of upward movement (termed 'potentiation'). As a measure of the efficiency of the pattern of forces of each jump the mean KE of the jumps of each subject were expressed as a percentage of the mean KE of the respective TMs. The group means of these measures were 75.8% for the CMJs and 72.6% for the SJs. Although this difference is small it was statistically significant at the 0.05 level. Thus, there was a tendency for the force patterns of the CMJs to be more efficient than those of the SJs. The increase or decrement in KE of the SJs with respect to the CMJs was attributed to three sources: The contribution due to the force pattern; the contribution due to using a different displacement range; and the difference due to force potentiation. It would seem that the displacement used and force potentiation have the major bearing on performance of SJs compared to CMJs and that the force pattern is relatively unimportant. However, it should be noted that in all jumps the pattern of forces did closely match the TM (as indicated by the work output (Figures 1a, 1b) with the biggest deficit occurring towards the end of the positive phase in all jumps. Therefore, within the physical limits of the performer, the pattern of forces was already close to the theoretical maximum. This does not imply that improvements cannot be made by improving timing, since timing also plays a role in potentiation of forces. In the light of the reviewed literature potentiation is dependent on timing the force output of the contractile units of the involved muscles to coincide with the maximum force output of the contractile units of the involved muscles to coincide with the maximum force output of the elastic components. Moreover, to be most effective, this summation of contractile and elastic contributions should occur late in the positive phase when the large vertical velocities of the CG en-

sure a large external power output. For 7 subjects a greater **KE** contribution due to force potentiation was achieved in the **SJs** than in the **CMJs**. This suggested that elastic energy was also being stored in the elastic components during **SJs** and that the **timing** of the jump was such that this elastic energy made a substantial contribution to external work.

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