DEPTH JUMP TRAINING AND THE VOLLEYBALL SPIKE

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THEORETICAL FRAMEWORK

The dynamics of movement often combine high strength demands with speed requirements. We speak of the rise time of a force, or the power (work done per unit of time) exhibited in the performance of a task. Success in numerous sports is dependent upon the ability to meet the strength-speed demands; and this practical need leads us to questions about how one improves dynamic capabilities. It has been suggested that plyometric training is a means to this end (Verhoshanski, 1968).

What is implied by the use of the term "plyometrics" is a type of exercise in which the rapid lengthening of a muscle under tension is immediately followed by a high velocity concentric contraction (Chu & Plummer, 1984). The intent of the exercise is to capitalize on reflex mechanisms and the mechanical properties of the fibers under stretch, thereby enhancing force production. Depth jumps (drop jumps or rebound jumps) are plyometric in design. To execute a depth jump means to drop from some specified height and upon landing immediately spring into a maximal vertical jump. Varying the height of the drop, or adding a static load increases the intensity of the exercise.

Depth jumps have been used in training programs to force maximal effort in the shortest possible time. It has been argued that such training increases the reactivity of the neuromuscular system (Verhoshanski, 1969), and results in improved product scores. With respect to the success of depth jump training as a strength development strategy, the experimental literature is inconclusive. The use of plyometric techniques in isolation may result in significant gains in jumping height (Blattner & Noble, 1979), but when used in combination with other strength training regimens no additional gains result (Clutch, Wilton, McGown & Bryce, 1983). Awaiting further strength development studies, it may be said that depth jumps, although not a superior training method, are potentially useful. However, if depth jumps are to be used as a generic training strategy for sports which require jumping ability, then it is also appropriate to investigate the congruence between the plyometric task and the sport-specific task. In other words, why would we expect depth jump training to enhance the jump performance in the volleyball spike? Out of our inherent belief in the specificity of training we asked questions of the similarity of performing a volleyball spike compared with a depth jump. Simple observation will make obvious the fundamental differences in the two performances. But our questions relate not to "what does the performance look like," but whether or not the two tasks utilize the same control strategies for enhancing dynamic force production capabilities.

We suggest that there are three means available for the enhancement of dynamic performance:

(1) Increasing muscle mass
By increasing the cross-sectional area of muscle tissue, the potential contractile power is increased.

(2) Exploitation of stored elastic energy
The capacity to store energy is a function of the structure of the material under stretch. In this case we are referring to the structural composition of the muscle fiber and tendinous attachments. The primary structures for the storage of elastic energy are the series elastic element and the cross bridge structures between the actin and myosin filaments.

(3) Utilization of reflex mechanisms
There are two subsets to this manner of force enhancement. First, there is the regulation of muscle stiffness. Our analogy for the operation of a muscle is a spring. The force exerted by that spring is a product of muscle stiffness and the magnitude of the stretch. Stiffness is modulated by tuning the muscle spindle; i.e., increased/decreased innervation (Crago, Houk, & Hasan; 1976). Second is the utilization of long latency reflex arcs. Whereas the myotatic reflex is the moderator of muscle stiffness, the long loop reflexes are related to motor unit synchronization. Milner-Brown, Stein & Lee (1975) and Hayes (1976) have suggested that the long latency reflexes are susceptible to training and may be the mechanism of strength development through increased motor unit synchronization.

Both increasing muscle mass and the potentiation of long latency reflex loops are training issues. They have been included in this preliminary discussion for the purpose of completeness of the theory. Where we really wish to focus our attention, however, is on the regulation of muscle stiffness and the use of stored elastic energy. Therefore, to refine our statement of purpose, it was our intention to look at the congruence between depth jump tasks and the jump involved in the volleyball spike in terms of the exploitation of readily available means to increasing dynamic force production capabilities.

THE EMPIRICAL INVESTIGATION

Methods

Three experienced female volleyball players participated as subjects for this study. All subjects used the "step-close" approach style to the volleyball spike. Table I summarizes the relevant anthropometric data for the subjects.

Subjects were filmed from the sagittal view using a 16 mm pin-registered Photosonics camera fitted with a 25 mm lens. Performance trials were filmed at an actual framing rate of 100 frames per second. The volleyball spike trials and depth jump trials were filmed on separate occasions, both filming sessions occurring in a laboratory setting. During filming of the volleyball spike, a net was erected and a volleyball was suspended from a support device above and in front of the net. During the performance of the depth jumps, subjects stepped off platforms of varying height and executed a rebound jump attempting a simulation of their volleyball spike.

Table I

SUBJECT CHARACTERISTICS

Subject	Age	Height (cm)	Weight (kg)	Vertical Velocity on VS approach $m \cdot s^{-1}$	Criterion* Height (cm)
1	22	181.6	71.2	1.0215	5.32
2	20	180.3	77.3	.9056	4.18
3	20	186.7	69.1	.8371	3.57

* Jump conditions will be designated as multiples of the criterion height.

In the first filming session, subjects performed multiple trials of the volleyball spike. On the basis of planar motion and the height of the jump, one trial was selected for subsequent analysis. Depth jump heights were determined after evaluation of the volleyball spike. For each subject, the vertical velocity of the center of mass at heelstrike of the penultimate approach step was used as the criterion for determining jump heights. The height necessary to achieve a given vertical velocity was determined by applying the kinematic equations of particle motion to the center of mass of the body, and assuming the constant acceleration of projectile motion (see Table I). Calculated jump heights were incrememted by a factor 5 times the criterion height. Platform heights approximated the calculated heights within a mean deviation of 2% (SD = 2.7%).

Three trials were filmed at each depth jump height with rest periods allowed between changes in height. Heights were incremented until the rebound vertical jump height began to decline. One trial for each depth jump height was selected for subsequent analysis. The trial selected was that trial which achieved maximum height of the whole body center of mass. Depth jump heights and rebound jump heights for each subject are reported in Table II.

Table II

VERTICAL JUMP HEIGHTS (cm) ACHIEVED

IN EACH JUMP CONDITION

	Subject 1		Subject 2		Subject 3	
	Vertical Jump Height	(Actual Drop Height)	Vertical Jump Height	(Actual Drop Height)	Vertical Jump Height	(Actual Drop Height)
Volleyball spike	44.25		47.26		40.04	
Depth Jump Conditions						
1 (criterion x 5)	42.0	(24)	36.2	(21)	43.6	(18)
2 (criterion x 10)	*42.9	(51)	*37.2	(42)	*45.8	(36)
3 (criterion x 15)	41.2	(80)	*37.1	(63)	*46.3	(51)
4 (criterion x 20)	38.2	(106)	35.2	(83)	42.6	(74)
5 (criterion x 25)			34.6	(106)	41.9	(89)
6 (criterion x 30)					42.0	(106)

* Best jump

The film was viewed through a projection system using a Lafayette analyzer and magnifying the image 75x. Coordinate data were obtained through the use of a Numonics digitizing system interfaced with a Univac 1182 computer. Standard computer programs were used to determine kinematic parameters including location of the whole body center of mass, selected segmental and intersegmental displacements and velocities, and absolute timing parameters.

Digitized landmarks included the metatarsal-phalangeal joint, lateral maleolus, and joint centers for the knee, hip, shoulder, and elbow. Displacement data were digitally smoothed using a second-order recursive Butterworth filter at a cutoff frequency of 6 hz.

Results and Discussion

Jumping performance product score. As expected, up to a critical value, the height achieved by the whole body center of mass increased as a function of increasing drop height (see Table II). Drop height beyond the critical value resulted in diminished vertical jumping performance. Although the critical value was specific to each subject, the optimal drop height ranged from 42 cm to 63 cm. This range is somewhat higher than the .4 m drop height reported by Asmussen and Bonde-Petersen (1974) as yielding best jump height. Nevertheless, we consider our data to be consistent with Asmussen and Bonde-Petersen in that their test heights were limited to .23, .4 and .69 m.

Stored elastic energy. Our first inquiry relates to the use of stored elastic energy as the facilitory mechanism, or control strategy, for enhancing force production. We know that when shortening follows immediately upon stretching, the force produced is enhanced (Cavagna, Dusman & Margaria, 1968; Bosco & Komi, 1979). Additional factors which are positively related to enhanced performance are velocity of prestretch, high force at the end of prestretch, and short coupling time between eccentric and concentric phases (Bosco, Komi & Ito, 1981).

Because this is not a kinetic analysis, we focused on two factors: (1) the velocity of the stretch, and (2) the coupling time between eccentric and concentric phases. Specifically to evaluate this control strategy, we looked at the angular velocity of the knee - the knee being a pivotal joint in any body projection and landing task. We suggest that a stored elastic energy control strategy may be evident in the characteristics of the velocity-time curve during ground contact.

In Figure 1 the angular velocity at the knee is plotted with respect to normalized time (percent of ground contact time). High velocity stretch may be observed in the magnitude of the angular velocity during the flexion phase. The coupling time is a function of the steepness of the slope of the curve between maximum velocity during flexion, through the time of joint reversal (zero velocity).

In Figure 2, the volleyball spike is plotted with the depth jump height which resulted in the best vertical jump, and with the curve corresponding to the maximum drop height. Of the three subjects, only for Subject 1 (S1) is the optimal depth jump a reasonable approximation of the volleyball spike. The magnitude of stretch velocity was slightly attenuated, but the similarity of the descending slopes, between peak flexion velocity through joint reversal, suggests that stored elastic energy was exploited to the same degree in both tasks.

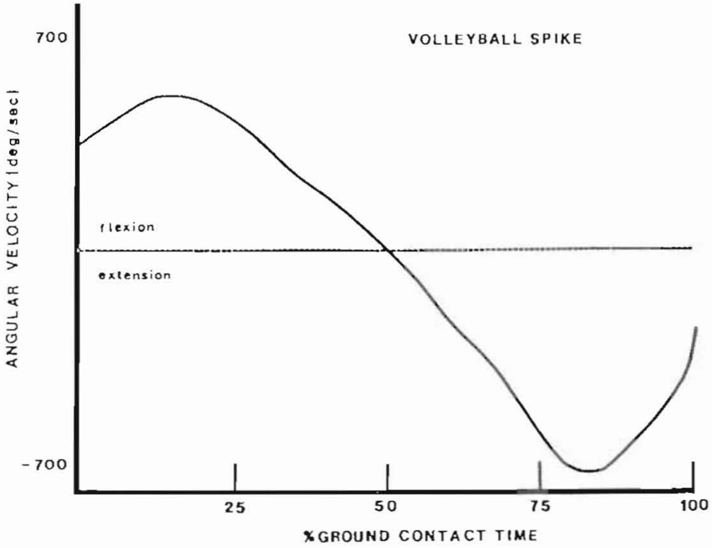

Figure 1. Angular velocity at the knee during ground contact

Note what happened in the jump which resulted from the maximum drop height (MAX). Initially, a very steep slope, but an extended flattening of the curve, is evident near joint reversal. This flattening may be interpreted as a lengthening of the coupling time between eccentric and concentric phases. This is manifested in stalling at the depth of the crouch which increases the probability of lost stored elastic energy.

Although all subjects displayed similar patterns for the volleyball spike, neither S2 nor S3 duplicated that pattern in the execution of the BEST depth jump. We would argue that these patterns are not indicative of exploitation of stored elastic energy.

According to our interpretation of the velocity-time curve, the slope pattern near joint reversal for the MAX depth jump of S3 is what we would expect to see. But the variability in the rest of the curve, and its deviation from the spike curve are indications that this jump fell apart. The magnitude of the drop height forced a movement adaptation to a pattern unrelated to the volleyball spike. Ideally, the curve should show no period of increasing slope between peak flexion velocity and joint reversal.

Regulation of muscle stiffness. Recall that the functional analogy is the muscle as a spring. The mathematical representation for the force of a spring is

$$\underline{F} = kx$$

where $\underline{F}$ is the force, k is the stiffness parameter, and x is the magnitude of the stretch. We know from the work in neural science and motor control (Asatryan & Fel'dman, 1965; Fel'dman, 1980; Gottlieb & Agarwal, 1979) that k, the stiffness parameter, may be consciously regulated.

Through EMG we might monitor the increased electrical activity of the musculature as an indication of increased muscle stiffness. But from an external view, we can identify other parameters as indicators of change in the stiffness factor. If displacements remained the same across two conditions, yet the resultant force increased, then one might reasonably assume an increase in k. That is, regulation of stiffness may be the control strategy used when there is an increase in the external impulse applied to the system. Evidence for this would be maintained, or small change in angular displacement, combined with decreased time over which the displacement was managed. Therefore, the variable of interest was the relationship between the angular displacement at the knee during flexion and the duration of the flexion or eccentric phase.

Figure 3 displays the flexion range of motion for the knee and the duration of the eccentric phase across increments in jump height. The angular displacement pattern at the knee followed a general trend across successive depth jump heights. Between footstrike and depth of the crouch, the eccentric phase, the trend was to increase the range of motion of the intersegmental angle at the knee. S1 and S2 showed a fairly linear trend in increasing angular displacement. Greater variability was evident in the pattern of S3, yet we suggest that the general trend may still be observed.

The time spent in the eccentric phase followed a different pattern. Typically after one or two height increments, there was a substantial reduction in the duration of the eccentric phase. Incrementing the drop height beyond this level was characterized once again by increasing durations.

What should be noted here is that the combination of increased angular displacement with a reduction in the eccentric phase resulted in the best jump. We argue that this combination is indicative of a control strategy which depends upon regulating muscle stiffness. In this respect S1 and S2 displayed a rather classic pattern. At the lowest step (first two steps for S2) the system established a baseline value. Perception of increased demands imposed through a higher drop height led to a resetting of muscle stiffness. In condition #2 for S1, angular displacement increased over condition #1, but the eccentric phase was substantially reduced. In the "muscle as a spring" model, reducing the eccentric phase with maintenance or small increase in displacement may be interpreted as a resetting of the stiffness factor, and results in increased force production capabilities of the muscle. For S1 the best jump height was achieved under condition #2. S2 also achieved one of her best jumps in condition #3 when increased angular displacement was combined with a substantial reduction in the eccentric phase. What is of interest is that for S2 and S3 comparable jumps (within .5 cm) were achieved with what appear to be different strategies.

For S2, note conditions #2 and #3. The difference between these jumps was within .5 cm, which is within measurement error. In condition #2 tight control over angular displacement is combined with an expanded eccentric phase. Yet in condition #3 spatial control is somewhat relaxed, but time compressed. The two jumps of comparable height for S3 are variable only in the spatial factor; the duration of the eccentric phase remaining relatively constant. For S3, jump condition #3 best exemplifies a stiffness control strategy with tight control over angular displacement and no significant expansion of time over the previous condition.

A decrement in jump height was characterized by increases in both the angular displacement and the eccentric phase. For S3, it appeared that spatial control was actually lost. In the last two jump conditions, S3 reached an anatomical maximum in knee flexion (38° and 37°). S1 and S2 were able to freeze the degree of knee flexion at maximums of 88° and 79° respectively.

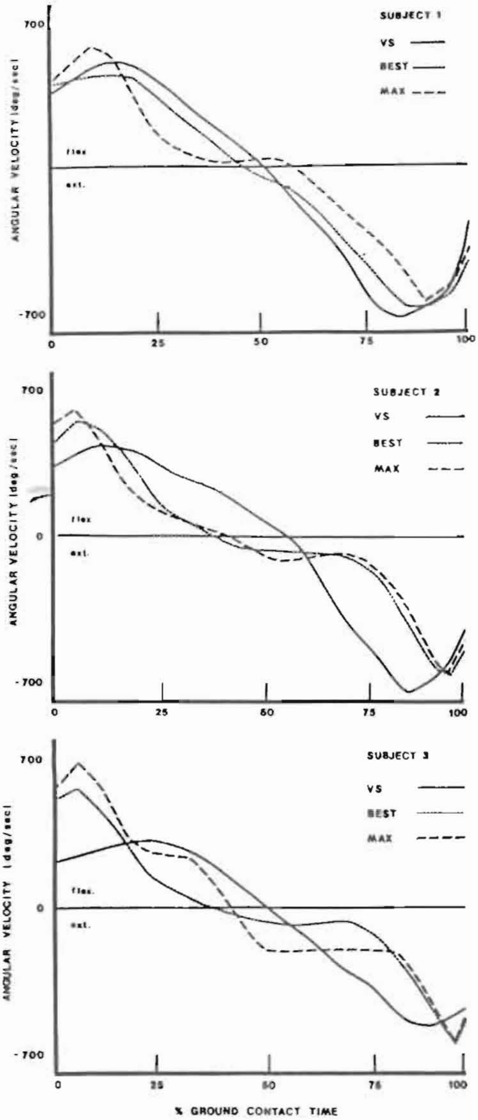

Figure 2. Angular velocity at the knee during ground contact for the volleyball spike (VS), the depth jump resulting in the best rebound jump height (BEST), and the depth jump from maximum drop height (MAX).

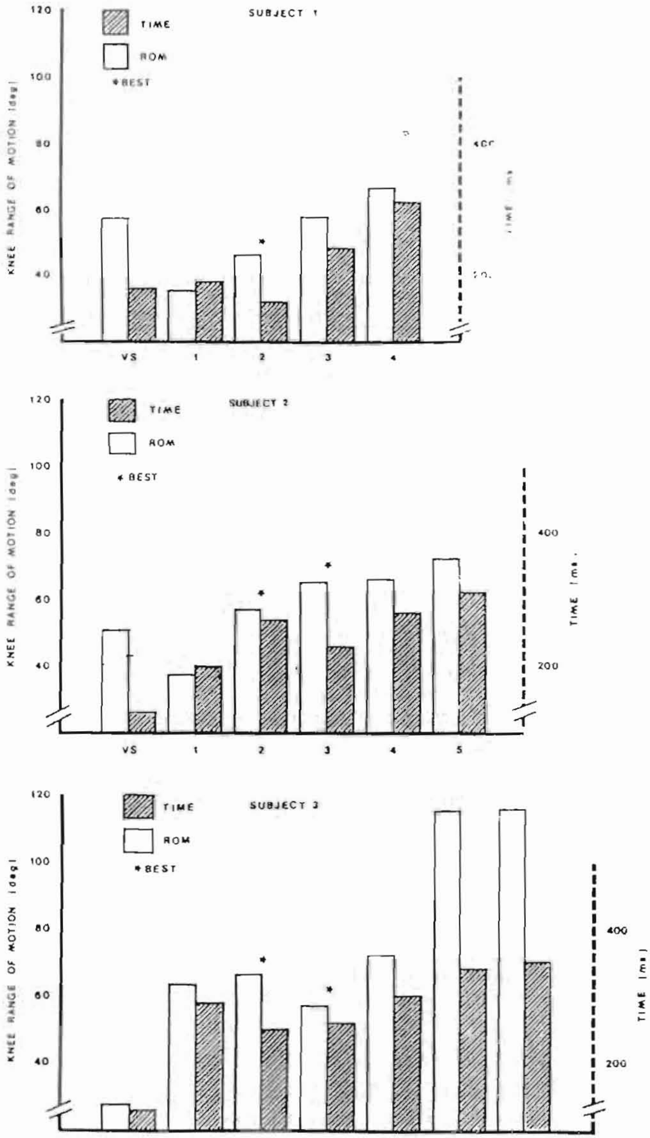

Figure 3. Range of motion at the knee during flexion and duration of the eccentric phase, as functions of jump condition.

SUMMARY

We return to our original question about depth jumps and jumps executed in the volleyball spike; do they really share the same critical parameters? Specifically, are these two tasks characterized by the same strategies for enhancing force production to achieve best height.

First, with respect to depth jumps, as height increases, the control strategy changes. At low to moderate heights, the perception of increased demands imposed through higher drop heights leads to a resetting of the muscle stiffness. But there is a critical value beyond which resetting the stiffness parameter is insufficient as an independent control. That is, the stiffness parameter is simply overwhelmed by the external impulse. All three subjects achieved a best depth jump height with a displacement-time pattern which would suggest a stiffness regulation strategy, but as two subjects demonstrated (S2 and S3) it is not the only strategy available.

Did the subjects use stiffness regulation in the execution of depth jumps and the volleyball spike? Referring again to Figure 3, S1 and S2 show relatively large displacements managed over short durations. So it appears that the two tasks may be executed in a similar manner utilizing a muscle stiffness control strategy.

From an external whole-body level of analysis, it is not possible to parcel out the roles played by stored elastic energy and muscle stiffness mechanisms. However, knowing the conditions under which stored elastic energy may be utilized allows us to identify when this method of enhancement is violated. So we characterize the optimum jump performance by high stretch velocities and short transitions between eccentric and concentric phases.

For two subjects (S2 and S3) the volleyball spike and depth jumps were controlled with different strategies (see Figure 2). We should note that for S2 the best depth jump height was 10 cm below the volleyball spike height. For S1, who appeared to take advantage of both stored elastic energy and stiffness regulation, the volleyball spike jump and the best depth jump were within 1.3 cm.

Among the three subjects we have seen evidence which suggests that under certain circumstances, both of these mechanisms have been the operant control strategy. For at least one subject (S1) both mechanisms appeared to be contributing to the success of the volleyball spike and the best depth jump.

We are not suggesting that we have accounted for all the strategies available for optimizing a jump performance. But to some extent, regarding stored elastic energy and muscle stiffness, we are saying that a jump is a jump. That is, both of these tasks are projection tasks; and in that sense, the performance of both would benefit from optimizing these control strategies to enhance dynamic force production.

From a study which began out of some skepticism that depth jumps were useful for volleyball players, we have come to the point of suggesting that depth jumps may be useful for teaching (if not for training). The regulation of muscle stiffness is a function of cognitive intervention. Utilization of stored elastic energy is related to technique. It should also be noted that when used as a teaching device, the use of extreme drop heights is contraindicated. Based on consideration of the strength of the individual subject, drop heights within the range of .4 to .7 m would in most cases yield optimal jump heights without disrupting the execution of the neuromuscular control strategies addressed here.

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