



## Original Article

## A Biomechanical Analysis of the Contributing Factors to Increases in Vertical Jump Height Following Exercise with Weighted Vests

Behdad Tahayori<sup>1,2\*</sup>, Arnold G. Nelson<sup>1</sup>, David M. Koceja<sup>1,2</sup><sup>1</sup>Department of Kinesiology, Louisiana State University, Baton Rouge, LA 70803, USA<sup>2</sup>Department of Kinesiology, Indiana University, Bloomington IN 47405, USA

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## ABSTRACT

**Background:** It has been shown that a bout of jumping exercise with weighted vests increases the subsequent countermovement jump height. However, it is not clear whether the improvement in jump height is due to the enhancement of joint power or due to other mechanisms such as neural adaptations.

**Methods:** To investigate this dichotomy, we tested the acute neuromechanical changes following a preloaded exercise protocol (3 sets of 5 consecutive CMJs with a weighed vest equal to 15% of the body mass of the participant) that successfully increased the subsequent jump height. On average, jump height increased 1.52 cm (5.40%) after this exercise as compared to CMJs prior to the exercise protocol.

**Results:** A significant decrease in the time from the start of the movement to take off (pre-take off duration) was observed. This decrease was exclusively caused by exercising with a weighted vest, since such a change was not observed in the control sessions in which participants exercised without the weighted vest. Our data showed that jumpers leave the ground with some degrees of knee flexion and upon exercising with weighted vest this amount of flexion increased and hence an increase in the jump height. However, no significant changes in peak values of lower limb joint angle, velocity, moment and power were observed.

**Conclusion:** It is suggested that for designing weighted vest exercise protocols with the aim of increasing jump height, the idea of modifying the timing of the movement should be considered as a cause of the enhancement. This novel idea adds another mechanism for increasing the jump height following weighted vest exercise, along with the general belief of muscle potentiation.

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### Introduction

Countermovement jumping (CMJ) is one of the most common physical activities used to assess athletic performance. This movement is an essential part of many sport activities, such as basketball and volleyball. Jump height CMJ becomes an important issue for athletic evaluation. Performing a light warm up prior to exercise

is believed to be effective for optimum performance. In addition, the type (active vs. passive) of the warm-up affects the subsequent performance [1,2]. It has been shown, for example, that acute passive stretches will decrease muscle power and jump height [3,4]. On the other hand, it is suggested that warming up with the same type of movement brings the optimum results for increasing CMJ height. This idea follows the theory of specificity which states that for enhancing any type of movement, the same movement type should be incorporated in the warm up [5]. Therefore, this method is becoming an accepted means for enhancing CMJ. In these warm up methods, athletes exercise jumping with an external load.

\*Corresponding author: Behdad Tahayori, Department of Kinesiology, Louisiana State University, Baton Rouge, LA 70803, USA, Department of Kinesiology, Indiana University, 1025 E. 7th Street, HPER 112, Bloomington, IN 47405-7109, USA, Tel: 1 812 8553714, E-mail: [btahayor@indiana.edu](mailto:btahayor@indiana.edu)

For example, the external load could be applied by using a Smith's machine [6], barbells [7] (various percentage of one repetition maximum) and/or weighted vests [8] (various percentages of body mass). Recent studies have shown the effectiveness of such warm up protocols for increasing CMJ height [8-12].

However, insufficient work has been done to compare the possible acute neuromechanical adaptations caused by exercising with weighted vests. It is expected that muscle activity and therefore power output increases after a warm up exercise with weighted vests through mechanisms such as post activation potentiation. Nonetheless no investigation has been done to examine an increase in hip, knee or ankle joint power after warming up with weighted vest protocols. Also, very little has been reported on the possible adaptations in jumping style and coordination after these warm up interventions. It is suggested by Vanezis et al. [13] that the main difference between good and poor jumping is the capability of hip, knee and ankle joints to produce more moment and power and the actual technique of jumping plays a less important role in performance superiority. This finding has not been confirmed for the cases of acute enhancement of jump height where the changes are temporary.

One gap that remains in the literature is the neuromechanical changes that occur in jumps after removal of the weighted vest. In this paper, we have performed a biomechanical comparison on CMJs prior to and after a warm up protocol with weighted vests. The results of this study provide insight into the mechanistic effects of exercise with preloaded vests and could be useful to those designing optimum protocols based on the mechanistic changes that they produce.

## Methods

Sixteen college students (9 male, 7 female) (age=21.71±1.20, body mass=64.41±16.26 kg and height=1.67±0.41 m) participated in this study. The procedure and the risks associated with the study were verbally explained to each participant. After accepting the procedures, they read and signed the consent form approved by the institutional board of review of Louisiana State University. None of the participants had a history of musculoskeletal disorder or severe or recurrent ankle sprains, as indicated by self-report.

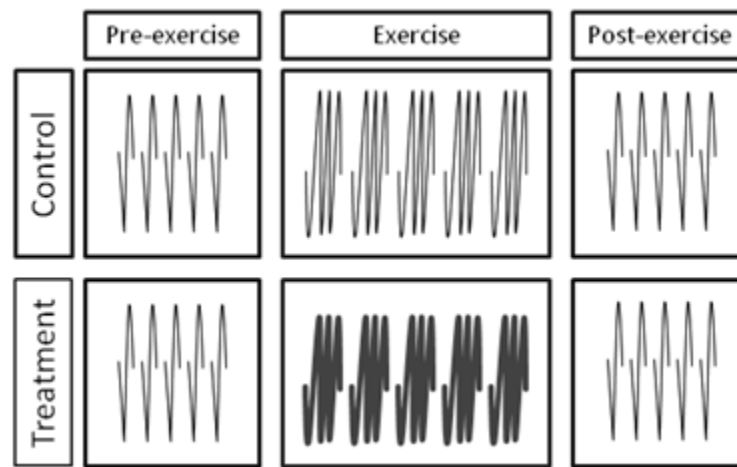
The study consisted of three sessions: one familiarization session, one control session and one treatment session. In the familiarization session the subjects practiced jumping to develop a stable pattern of countermovement jump and become oriented with the procedures and phases of the experiment. A string was hung from the ceiling right in front of the subjects. Three adjustable paper markers (targets) were attached to the string. One target was placed on the very top part of the string at a distance that could not be reached by jumping. Subjects used this target as the goal to reach while jumping. The purpose of this target was to increase motivation and reinforce the goal of jumping as high as possible on each trial. The other target was adjusted to the subjects' eye level in full




upright position and the lowest target was adjusted at eye level when bending the knee to approximately 75 degrees of flexion. During the familiarization session they were asked to practice in a way that precluded dipping down lower than the second target. This warranted that the subjects developed a reliable pattern of movement and any changes in angles during data collection sessions were not due to the inconsistency of movement.

Control and treatment conditions were randomly assigned to subjects. Each condition was preceded by a light warm up exercise. This warm up consisted of 5 minutes of treadmill walking and a few countermovement jumps with moderate effort. At the control condition subjects initiated the experiment with five separate countermovement jumps with a 30 second interval between each. After two minutes of rest, they performed five sets of three consecutive countermovement jumps with maximum effort. Then, after two minutes of rest, they jumped for five more times. The treatment condition consisted of the same sequence as that of the control with the difference being that during the 5 sets of three consecutive jumps they wore a weighted vest (GoFit®) equal to 15% of their body mass. A schematic of the two conditions is presented in Figure 1. Body center of mass (BCOM) of the defined model was calculated for each subject.

For data collection sessions, all participants jumped with the same type of shoe (SAUCONY®) to avoid any possible bias in shock absorptions caused by the properties of different shoes. Vicon® motion capture system was used to collect kinematic data with the frequency of 120 Hz. One AMTI forceplate was used to collect ground reaction force. For the aim of inverse dynamic analysis, subjects stood with one leg in contact with the plate. This ensured proper calculations of joint moments and joint powers. Therefore all kinetic and kinematic calculations were performed for the right lower limb. Kinematic data were filtered using a 3<sup>rd</sup> order Butterworth low-pass filter with a 6 Hz cutoff frequency. The biomechanical model consisted of twelve rigid body segments. Tracking retro-reflective markers were placed on each segment to reconstruct a 6 degree of freedom motion of the segments. These markers were placed on head (two on the sides and two in front), C7, proximal ends of clavicles, both shoulder joints (Acromion process), medial and lateral elbow and wrist of both upper extremities, ASIS and PSIS of both sides, both thighs and both shanks using cluster markers (four on each cluster). Five markers were permanently placed on each shoe on the heel, toe box, lateral side of quarter, medial and lateral border between the vamp and toe box. The proximal and distal ends of each segment were defined by calibration markers. Total body center of mass was calculated from the defined model of 12 segments. Jump height was determined from vertical displacement of body center of mass from toe off to peak.

The elapsed time between the initiation of movement and toe off was regarded as pre-take off duration. For the sake of analysis, as suggested by Hatze [14], this duration was divided into preparation and propulsion phases. Preparation was defined as the duration between the start of the movement to the lowest position of center of



**Figure 1:** Data collection consisted of two conditions: Control and Treatment. Each conditions had three blocks (sessions): pre-exercise, exercise and post-exercise sessions. The two conditions differ in their exercise sessions.  shows one CMJ,  represents three consecutive CMJs and  represents exercising with weighted vest.

mass, whereas the propulsion phase started immediately after preparation and ended at take off. Joint moments and powers were normalized to total body mass. Total body mass for the preloaded situation was considered as body mass plus the mass of the vest. The dependent variables to compare these jumps were jump height, initial velocity at take off, duration of pre-take off phase, hip, knee and ankle joint angle, velocity, moment and power. All calculations were performed by Visula3D® software (C-motion Maryland, Baltimore).

#### Statistical Analysis

A  $2 \times 2 \times 2$  (Condition $\times$ Time $\times$ Gender) ANOVA was performed on the dependent variables with repeated measures on condition (treatment vs. control) and time (pre vs. post). Gender served as the between-subjects effect. In the case of significant interactions, Bonferroni corrections for multiple pairwise comparisons were applied. The assumption of sphericity was not violated for any of the dependent variables.

#### Results

The ANOVA revealed a significant Condition  $\times$  Time interaction ( $F(1,14)=4.90$ ;  $P=0.043$ ). Post-hoc comparisons revealed that jump height increased significantly from pre- to post-test in the treatment condition ( $P=0.001$ ), but it was not significant for the control condition ( $P=0.71$ ). Jump height for the pre and post exercise sessions of the control condition were 28.74 and 28.82 cm respectively, while the values for the treatment condition were 28.10 and 29.63 cm respectively. Therefore the increase in jump height was 1.52 cm (5.40%) in the treatment condition (1.88 cm for men and 1.15 cm for women). The remaining interactions and main effects were not significant ( $P>0.05$ ).

Men's jump height in this study was 34.57 whereas it was 21.47 for women. The test for between subjects effects showed a statistically significant difference between the jump height in genders ( $F(1,14)=11.50$ ;  $P=0.004$ ).

However, since there was no interaction between time and gender, the two genders demonstrated the same trend of reaction to the experimental setting.

Comparison of peak values of hip, knee and ankle joint angle, velocity, moment and power did not show any statistically significant difference between pre and post exercise sessions in either of control and treatment conditions. Summary of these values are presented in Table 1.

Comparison of initial velocity showed a statistically significant increase from pre-exercise session to post exercise session in the treatment condition (2.25 to 2.35 m/s respectively). No significant changes were observed in the initial velocity between pre and post sessions in the control condition. As was expected, the results are consistent with the findings of jump height. Initial velocity is a manifestation of the height one can jump and is the net resultant of the force exerted on the ground. Statistical analysis of the timing of jumps in different conditions showed that the total pre take-off duration decreased significantly in post-exercise situation relative to pre exercise situation of the treatment condition (0.822s Vs 0.794s).

The preparation phase of pre-take off duration was shorter in the post exercise situation of the treatment session compared to pre exercise situation. A summary of these results is presented in Table 2.

Significant increase in knee flexion angle and angular velocity of 3.91 degrees and 2.76 deg/s were observed during the post exercise session of treatment condition ( $P=0.003$  and 0.0001 respectively). Ankle angle and angular velocity increased significantly in post exercise session of the treatment conditions for 2.29 deg and 6.25 deg/s ( $P=0.001$  and  $P=0.0001$  respectively). Other parameters did not show a statistically significant difference.

#### Discussion

The designed protocol of this study, namely warm-up

**Table 1:** Peak values of hip, knee and ankle joints angle, moment, power and velocity for both treatment and control conditions. No significant change was observed among different conditions/situations. SDs are written in parentheses

Variable	Joint	Control		Treatment	
		Pre	Post	Pre	Post
Angle (Deg)	Hip	-80.55 (11.19)	-82.38 (10.70)	-84.41 (11.86)	-84.35 (12.42)
	Knee	90.33 (9.84)	90.60 (9.67)	96.96 (11.87)	97.09 (10.10)
	Ankle	35.78 (4.96)	35.65 (5.57)	38.12 (5.99)	37.81 (5.32)
Moment (Nm/kg)	Hip	-1.40 (0.27)	-1.46 (0.28)	-1.48 (0.37)	-1.55 (0.41)
	Knee	1.44 (0.56)	1.33 (0.51)	1.44 (0.31)	1.48 (0.34)
	Ankle	-1.24 (0.23)	-1.27 (0.17)	-1.30 (0.19)	-1.31 (0.20)
Power (W/kg)	Hip	4.61 (1.56)	4.79 (1.86)	4.81 (1.45)	4.84 (1.52)
	Knee	6.35 (2.40)	6.37 (2.11)	7.46 (2.63)	7.42 (2.79)
	Ankle	6.20 (1.83)	6.03 (1.49)	6.47 (1.83)	6.44 (2.02)
Velocity (Deg/s)	Hip	263.94 (55.15)	262.84 (38.88)	258.12 (45.05)	264.52 (45.52)
	Knee	714.81 (64.33)	707.89 (62.77)	676.53 (72.66)	688.76 (66.67)
	Ankle	-739.45 (104.82)	-724.30 (104.41)	-683.93 (75.92)	-699.00 (78.32)

**Table 2:** Timing of phases of the jump in different conditions of jumping in seconds. § indicates significant difference between post and pre situations

Phase	Control		Treatment	
	Pre	Post	Pre	Post
Preparation	0.54	0.53	0.55	0.53* P=0.042
Propulsion	0.26	0.26	0.27	0.26
Duration	0.81	0.80	0.82	0.79* P=0.035

\*Indicates significant difference between post and pre situations

with weighted vest, resulted in a significant increase in jump height. The comparison of the same exercise without the vest failed to produce any substantial change in the subsequent jumps. This comparison ensures that the changes observed in the treatment condition were predominantly due to exercising with the vest and not simply due to the performance of consecutive jumps. This protocol increased the jump height on average 1.52 cm which was 5.40% increase in the jump height.

The main biomechanical changes between pre and post exercise jumps were the decrease of pre-take-off duration and increase of knee and ankle angular and knee flexion angle at take-off. There were no statistically significant changes in the peak values of joint parameters between post (higher jump) and pre-loaded conditions. Therefore, we failed to confirm that the acute enhancement of jump was due to changes at individual joint level after the treatment. This was an unexpected finding, but points towards other factors (perhaps neural) that may be involved in enhancement of movement.

It has been shown that good jumps are correlated to joint power output. Vanezis and Lees [13] conducted a biomechanical analysis to compare good and poor jump

performers. They suggested that the difference between good and poor performers is due more to the power output of the joints than the technique of the athletes. As such, it can be inferred from findings that for persistent increase of jumping performance, the emphasis should be on strengthening exercises of the lower limb. In contrary, our results suggest that an acute increase in jump height is primarily caused by a decrease in the duration of the countermovement jump after removing the weights. This interpretation is in agreement with that of Cavagna et al. [15] who found that increase in height of countermovement jump when compared to squat jump was more related to a decreased time in which positive work was done rather than an increase of positive force. Although the sequence of eccentric-concentric contraction was shortened in the post weighted exercise jumping, no increase of joint output was observed in the positive phase of the jump (the concentric contraction part). Given that joint angles and moments were not changed, it can be inferred that torque-angular velocity and torque-angle relations were not altered. Therefore, it is improbable that the reduction of time observed enhanced the stretch-shortening cycle and hence increased power output. These findings were

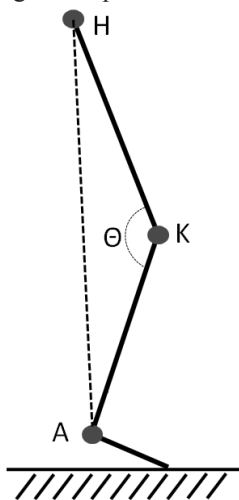


surprising and did not match with the expectation that enhancement of jump is due to the increase in power output of the joints. Thus, the question that needs to be addressed is: how is it possible to increase jump height without the necessity of increasing work output?

The problem can be analyzed from the optimization of degrees of freedom during the pre-take off phase which will result in a mature toe-off. One can easily comprehend that the rotations at all lower limb joints are translated to a linear motion of the center of mass. During jumping, joints rotate to linearly move the center of mass as upward as possible. For this translation both geometrical and anatomical constraints heavily influence the final height one can reach. As has been shown by Van Ingen Schenau et al. [16], and has also been observed in our data, jumpers leave the ground before fully extending the knees. The reason for this is that the transfer of angular velocity of the lower limb to a linear velocity of the center of mass is related to both knee angle (geometrical constraint) and knee angular velocity (anatomical constraint). This can be formulated as follows based on a chain differentiation of change in lower limb length from hip joint to ankle joint (Based on a model proposed by Van Ingen Schenau [17]).

$$V_{HA} = dHA/dt = \underbrace{[HK \times KA \times \sin(\theta)]}_{\text{Geometrical}} / \underbrace{[HK^2 + KA^2 - 2HK \cdot KA \times \cos(\theta)^{1/2}]}_{\text{Anatomical}} \times d\theta/dt \quad (1)$$

Where  $V_{HA}$  is the difference in the velocity between hip and ankle, HK and KA are thigh and shank lengths respectively and  $\theta$  is knee angle (Figure 2). Since the sine of 180 degrees is zero, it is clear that at full extension the linear velocity approaches zero. The expression in the bracket is regarded as the geometrical constraint whereas the angular velocity is the anatomical constraint. Therefore, here we face a constraint optimization problem. Timing and sequence of the movement is highly critical for the optimization of this movement. Other modeling and simulation studies of jump height have also shown that timing has a great impact on the final jump height [18].



**Figure 2:** Linked-model free body diagram of hip, knee and ankle during take-off. The change in HA is dependent on both knee angle and angular velocity. H=Hip joint center, K=Knee joint center, A=Ankle joint center.

We have observed that in the post exercise session, subjects jumped with less extended knees (geometrical constraint) and higher knee angular velocity (anatomical constraint). Also it was shown that ankle angular velocity was increased which assists in the final upward movement of the center of mass. Therefore, we assume that exercising with the vest has affected the timing (or relative timing) of movement in favor of an early induced optimized take-off. This novel idea introduces a new possible mechanism for acute increase in jump height following jump exercise with weighted vest. Further research is needed to strengthen not only this idea but to also answer the question that whether other methods which have been shown to be effective in increasing the jump height entails the same mechanism. However, the results of current study put forward this idea that along with other proposed mechanisms, one effect of exercise protocols with loaded vests could be the acute enhancement of jumping coordination and timing. Therefore, it can be assumed that the duration and the amount of load for such dynamic exercises should be adjusted in a way to induce the changes of timing while avoiding fatigue.

Although our results of jump height enhancement is in agreement with most, but not all, studies done on dynamic exercise with loaded vests, the amount of load used in reported studies is not consistent. For example Thompsen et al. [8] reported a 5.30% increase in vertical jump height following an exercise protocol with loaded vest equal to 10% of body mass with a greater number of repetitions. Therefore they observed almost the same percentage of height increase with 5% less weight. Faigenbaum et al. [9] compared 4 exercise protocols with and without weighted vests and suggested that exercise with a vest weighted with 2% of body mass is more effective than a 6% vest in their group of 20 female high school athletes. Future studies are needed to investigate the optimum load/duration coupling for these types of warm up protocols, but the findings of the current study do increase the understanding about the mechanisms of the effectiveness of exercise with loaded vests. However, the effect of increasing the number of repetitions is a matter for further research. From the current study, it cannot be inferred whether increasing the number of repetitions or the amount of load, will result in changes at joint levels.

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