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Effect of Using Hand-Weights on Performance in the Standing Long Jump

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Abstract

Previous standing long jump studies have shown that jumping with hand weights can significantly increase jumping performance. The purpose of this study was to investigate the mechanisms that enable performance improvement in the standing long jump when using hand weights and test the hypothesis that releasing the hand weights during flight can further increase jump distance. Four college-aged male subjects were chosen based on participation in athletic activities and physical ability. Each subject executed 24 jumps (six trials for each of four different standing long jump techniques: without weights, with weights, releasing the weights backwards near the high point of the jump, and releasing the weights just prior to landing). Joint positions were recorded using multiple high-speed cameras and reflective position markers on the body. The net joint moments were calculated using a 2D inverse dynamics analysis. An energy analysis of the system between jump initiation and takeoff was also performed. Results showed jumping with weights increased jump distance by an average of 9 cm while releasing them increased jump distance by another 7 cm. No significant difference in jump distance was found between the two release points. The mechanisms that enabled this performance improvement were a combination of increased kinetic energy stored in the hand weights before the propulsive phase, increased work performed by the muscles during the propulsive phase, and an increase in horizontal position of the center of mass at take-off. In addition performance was enhanced by releasing the weights backwards during flight due to conservation of linear momentum during the flight phase.

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1 Introduction

The standing long jump dates back to ancient Greek times when it was used as a performance measure for athletes in the Olympic Games. Pictographs have been found depicting the athletes performing standing long jump-like maneuvers and some Olympians were even found buried with halteres (hand-held weights) which were used presumably to increase performance and distance of the jump (Minetti and Ardigo, 2002). Many researchers have analyzed the standing long jump in order to determine what performance characteristics have the greatest effect on overall distance. One such characteristic of performance is the effect of arm motion on jump distance and mechanics. Studies have shown that coordinated arm motion plays a significant role in jump performance (Ashby and Heegaard, 2002; Lees et al., 2004; Cheng et al., 2008; Wu et al., 2003; Hay, 1993). It has also been found that jumping with halteres (hand-held weights) can further increase that jumping performance (Ashby, 2005; Minetti and Ardigo, 2002; Tang, 2007; Huang, 2003; Papadopoulos et al., 2011; Lenoir, 2005). Researchers have hypothesized (Minetti and Ardigo, 2002) and simulated (Ashby, 2005) that even more distance could be obtained if the jumper throws the weights backwards during the flight phase of the jump. Simulations do not always translate into real life situations however, as during simulations assumptions are made for simplification. Limitations of the human body and coordination are factors that often are difficult to model in simulations. It is possible that the average human might not be coordinated enough to execute the jump as it is simulated and results would not be improved by releasing the weights during the jump. Studies have shown coordination can sometimes be of greater importance to jump performance than the dynamic force production (Aguado et al., 1997). A limited research study has investigated the effects of releasing weights mid-flight with human subjects (Huang et al., 2003), but results were only compared between jumps with no weights and jumps with releasing the weights during flight. In that study there was no evidence to be able to determine if releasing the weights added any performance improvement over retaining the weights for the entire jump.

The mechanisms that enable performance improvement in the standing long jump using hand-held weights have not been fully elucidated. This study aimed to further investigate the effects hand-held weights have in order to answer the five research questions proposed below.

1) How much does performance improve in the standing long jump when jumping with hand-held weights?
2) Does releasing weights during flight increase jumping distance? If so, by how much?
3) What is the optimal release position of the weights during flight?
4) Do results reflect that of simulation studies?
5) What are the mechanisms that enable performance improvement in the standing long jump when using hand weights?

A human subject experiment was designed to answer these through examining four different jump techniques: without weights, with weights, releasing the weights backwards near the high point of the jump, and releasing the weights just prior to landing. To do this, the subjects were recorded jumping using a motion capture system which recorded positions of markers placed near the body’s joints. This data, along with force plate data was used to calculate joint torques, joint powers, work done by the joints, work done by the entire body based on differences in kinetic and potentialenergies between initiation and takeoff, center of mass position, and center of mass velocity at takeoff. These performance parameters were examined in order to see how they work together to enable performance improvement.

2 Background

Several researchers have analyzed the biomechanics of human jumping involving arm motion analysis. From this research, it has been shown quite clearly that the use of coordinated arm motion during a standing long jump increases jump performance. This result is explained in part by three main theories: joint torque augmentation theory, impart energy theory, and hold back theory (Ashby and Delp, 2006). These theories (described in more detail later) help explain the mechanics and performance of the body during the jumping motion. The following section outlines the results of the major research investigations into the mechanics of human jumping.

2.1 Vertical Jumping Studies

Nagano et al. (2008) developed computer simulations of human vertical and horizontal countermovement jumps that focused mainly on the orientation of legs and hip. The main purpose was to determine the optimal jumping technique for both vertical and horizontal jumps and analyze the differences in joint torques between the two. The study found that there was a greater torque around the hip in the horizontal jumps than in the vertical jumps, which was needed to move the trunk of the body forward. It was also found that the time elapsed during the preparatory countermovement of the horizontal jumps (0.92s) was longer than that of the vertical jumps (0.65s).

In 1999, a jumping study was published in which 25 volleyball players performed countermovement vertical jumps with and without arm motions to determine the contribution of the arms (Feltner et al., 1999). Results showed the jumps with an arm swing had a greater vertical velocity and height of the body's center of mass at take-off, resulting in greater jump heights for the arm swing vs. no arm swing jumps. The increase in height of the body's center of mass at take-off contributed 43% of the total increase in performance while 57% was due to the increased velocity of the center of mass at take-off. Examining the lower extremities, it was found that arm-swing jumpers exhibited higher hip and knee extension torques with a decrease in the angular velocity at key times. This was coupled with a decrease in the rate of counterclockwise rotation (with respect to the trunk's center of mass with the subjects facing to the right) of the trunk as the arms began their motion. This was due to the swinging of the arms inducing a downward force at the shoulder. This downward force generated a clockwise moment about the trunk's center of mass, slowing the rotation rate. This concept is known as the joint torque augmentation theory which states that swinging the arms during the propulsive phase of the jump creates a downward force on the trunk and slows the extension velocities of the lower body joints, thus enabling the lower body muscles to generate more force due to the their lower contraction velocities. According to the force-velocity properties of muscle, more force can be generated at slower contraction velocities. No significant differences in the kinematic and kinetic data at the ankle resulted from the presence or absence of an arm swing.

Other vertical jump studies have been conducted showing similar results to the Feltner study but expanded upon the analysis of the biomechanical mechanisms that drive performance (Lees et al., 2004; Cheng et al., 2008). In the study by Lees et al., the purpose was to examine some common theories explaining why arm motion increases jump performance (joint torque augmentation theory and pull theory). From the investigation, it was found that the pull theory, which states that towards the later part of the jump, when the arms begin to decelerate, their high vertical velocity relative to the trunk enables them to pull on the trunk by transferring energy from the arms to the rest of the body, was found to be true. Power generated by the arm muscles was transferred to the rest of the body increasing the kinetic and potential energy of the system at takeoff. The study found the pull theory to be the prevailing reason behind the increase in performance and that joint torque augmentation had little effect. The Cheng study found slightly different results which substantiated both the joint torque augmentation theory and pull theory. The Cheng study was a computer simulation study only however, instead of a human subject study. From the results it was concluded that about 50% of the performance increase was attributed to each theory.

2.2 Previous Standing Long Jump Studies without Weights

For horizontal jumping, in the early 2000s more specific studies exploring the mechanisms of the standing long jump using a motion capture system were published (Ashby and Heegaard, 2002; Wakai and Linthorne, 2005; Wu et al., 2003). The purpose of the Ashby and Heegaard study was to determine the differences in standing long jump performance between jumps with free arm motion and jumps with restricted arm motion. The study found that the subjects jumped an average of 21.2% farther with free arm motion. The majority of this was due to the increase in takeoff velocity of the center of mass. The rest was due to an increase in the horizontal and vertical displacement of the center of gravity before takeoff. For the subjects with restricted arm motion, it was found that prior to take off, there was a premature decline in the vertical ground reaction force resulting in a backward rotation moment about the center of mass. It was postulated that this was necessary for them to maintain balance throughout the jump and land properly without using their arms. This explanation of one reason why performance is reduced without arm motion was defined as the “hold back” theory.

The objective of the Wakai and Linthorne study in 2005 was to determine the optimum take off angle for the standing long jump. Previous studies have shown the preferred projection angle for take-off for adult males in the standing long jump to be anywhere from 29-38°. However, the calculated optimum take-off angle in the study was found to be 19-27°. Both are much lower than the 45° angle expected for projectile motion. In the study, the subjects were asked to perform jumps at a variety of take-off angles both higher than they preferred and lower. It was found that take-off speed decreased with higher take-off angles, which resulted in reduced jump distances. In the study, there was less data available for take-off angles less than 25°, and as a result, the curves were extrapolated. It was found that performing a jump at the precise optimal take-off angle was not as critical to jump performance as was expected. The take-off angle could be within +/- 5° of optimum with a resulting difference in distance of no more than 2 cm. There were three main factors causing the optimum take-off angle to be below 45°: the relation between take-off angle and take-off speed, the difference in height of the center of mass between take-off and landing, and the horizontal distance gained from leaning farther forward at take-off.

Wu et al. (2003) performed a standing long jump study to determine the effects of arm motion and initial knee angle on performance using ground reaction force analysis and three dimensional motion analysis. In this study, 34 females performed a series of jumps with and without arm motion as well as varying initial knee angles (45 and 90°). Results showed again that arm motion jumps were longer. It also showed that the jumps with a 90° initial knee angle were 1.2 times longer than jumps with a 45° initial knee angle. This study found that take-off angle did not play a huge factor in jump performance and anthropometric factors did not always dictate performance (i.e. having longer legs did not necessarily mean better performance). It was concluded that proper coordination and technique of using preparatory countermovement and arm motion was more important than muscle mass and height. Basically, smaller people who efficiently use their arms can jump farther than taller stronger people who do not use their arms.

Arm motion analysis in the standing long jump has also been analyzed in a simulation study (Ashby and Delp, 2006). In the Ashby and Delp study, optimal control simulations were developed to find the joint torque activations that maximize performance for jumps with free and restricted arm movement. The objective was to use these simulations to analyze the mechanisms behind the performance improvement gained from free arm motion while jumping. From the results, it was found that all three main theories (hold back, impart energy (also known as pull theory), and joint torque augmentation) were supported by the simulations. The hold back theory was supported in that joint activations had to be limited during the propulsive phase to allow the segments to be properly positioned for landing. Joint torque augmentation occurred in that the arm swing resulted in reduced extension velocities of the lower body joints and thus augmented the ability of the lower body joint torque actuators to generate torque and perform work. The impart energy theory (or pull theory) was also supported as during the free arm motion jumps, the total energy of the system was increased by the extra work done at the shoulder. All three of the theories were shown to increase the horizontal and vertical velocities of the center of mass of the system at take-off with the most significant contribution coming from the additional energy imparted to the system by the work done by the shoulder actuator.

2.3 Simulation Studies for Standing Long Jump with Hand-held Weights

Several researchers have found that using hand weights while jumping should increase jumping distance (Tang and Huang, 2007; Ashby, 2005; Minetti and Ardigo, 2002). This is not a new concept. Investigators have performed computer simulations to show how weights can be used to increase performance. The computer models that were generated by Minetti and Ardigo showed that using weights in the standing long jump should increase a 3 meter jump by at least 17 cm. The main reason for the increase in distance with weights was suggested by Minetti and Ardigo to be due to the joint torque augmentation theory. Using weights accentuates this phenomenon enough to compensate for the increase in mass of the system. They also postulated that throwing the weights backwards would increase distance even further. This is due to the fact that the path of the center of mass of the total system does not deviate from its parabolic trajectory during flight and throwing the weights backwards would propel the body forward in order to maintain that path for the entire system. The researchers suggested that the release point of the weights would be just before landing as the arms are swinging back down as this is how it was depicted in ancient Greek vase paintings. Minetti released another paper two years later (Minetti, 2004) that also describes the performance improvement that can be derived from jumping with weights and how similar concepts can be used in other athletic feats such as ice hockey or even forms of locomotion such as human propelled flight using airfoil-bicycle-propeller planes.

An optimal control simulation study was performed by Ashby (2005) to further investigate the effect of hand-held weights on jump performance. It compared a jump without weights, a jump with weights, and a jump with releasing weights during flight. Five total weight cases were run (4, 6, 8, 10, and 12 kg). The simulation results concluded that the best weight for optimum flight distance was 8 kg and the best jump type resulted from releasing the weights during flight. In these simulations, the total jump distance for jumping with weights improved performance by 39 cm when compared to jumping without weights (2.35 m to 2.74 m), much higher than the 17 cm calculated from the Minetti and Ardigo study (2002). In addition, releasing the weights during flight increased the jump an additional 15 cm for an optimum jump distance of 2.89 m. This study also indicated that the optimum release point was over the head as the jumper reached peak height at around 0.18 s after takeoff. When releasing the weights just before landing, the total jump distance was only increased by 1 cm over retaining the weights the entire time.

2.4 Human Subject Jump Studies with Hand Held Weights

A study was performed to investigate the validity of some of the athletic feats described in Greek lore, specifically the story pertaining to the 50 ft jump by Phayllos (Lenoir, 2005). Prior research had postulated possible answers to how this could have been possible with suggestions such as the landing area being around 5.5 m below the take-off area or, more plausibly, the jump performed was similar to the modern triple jump with a run up (Ward-Smith, 1995). It was suggested from the paintings on vases describing the story that Phayllos performed this feat using hand-held weights to increase performance. In the Lenoir study, it was found that the most likely explanation would be the jump came from a five-fold jump, where the athlete regained his balance after each jump and prepared again in the same manner for each jump, basically doing five standing long jumps in a row. This was tested with an experiment with four college physical education students who performed both continuous five-fold symmetric jumps and singular standing long jumps with and without weights. The athletes trained for this for eight weeks prior to the data collection and the data collection was spread over a week's time to reduce fatigue factors. Results showed a 5.5-6.0% gain on average for jumps with weights over jumps without. In addition some subjects jumped as far as 15.63 m (51.3 ft) making the Phayllos jump an acceptable possibility.

Other researchers of the ancient Greeks have studied the topic and found results suggesting only the athletically inclined would benefit from using hand-held weights while jumping (Thaller et al., 2003). In the Thaller study, seven subjects performed movements with maximal voluntary effort as described by a mathematical model (Sust, 1996) and comparing that to simulations of the seven subjects performing vertical jumps with and without 2 kg weights in each hand. The movements involved the subjects lying on their back and accelerating an external load vertically with their legs. The same method was used for measuring the force produced by the arm extensors. The parameters representing the individual properties of the knee extensors were found by non-linear parameter estimation as described in the Sust study. In the simulations, it was found that the movement caused by the arms decreases the velocity of knee extension causing the force in the legs and energy of the jump to increase. This relationship was found to be non-linear when compared to their maximal force production in the knee, depending upon each subject's anthropometric quantities and the additional weight added. Results showed that not every subject benefitted from the additional weight. It was concluded that the stronger subjects yielded greater benefit from using the weights in the jump since they could add more kinetic energy to the system whereas the weaker subjects could not overcome the additional mass that the weights added to the system.

Tang and Huang (2007) performed a human subject study to confirm the effects of using hand-held weights to increase distance suggested by previous simulation studies (Minetti and Ardigo, 2002; Ashby, 2005). Eight male collegiate athletes performed jumps with no weights, light weights (2-4 kg), heavy weights (6-8 kg), and extra heavy weights (10-12 kg). Results indicate that jumping with weights increased jump distance and horizontal impulse during takeoff for all loading conditions with heavy loading (6-8 kg) yielding optimal results. The vertical takeoff velocity of the center of gravity however, decreased with all loads. Although landing distance increased when jumping with weights over no weights, the landing posture was altered and the center of mass of the subject was farther back at landing. No mention was given to how this posture change affected performance. They postulated that the increase in horizontal impulse was due to increased muscle force but provided no suggestions as to what caused that increase in muscle force. This increase in muscle force was concluded to be the main contributing factor in the increased jumping distance. They suggest that the optimal weight to be 5.3% of total body weight. The subjects in this study retained hold of the weights throughout the entire jump however, and no speculation was given on the effect of releasing weights during jumps.

Huang et al. published studies in 2003 and 2005 which investigated some other effects from jumping with weights including releasing weights during flight. In the 2003 study, the subjects performed jumps without weights and jumps where the subjects released the weights at the peak height of their jump. Eight male subjects were tested, each using two different sized dumbbell sets randomly assigned ranging from 0-12 kg. Each subject jumped six times: two without weights and two with each different randomly sized dumbbell set. Of the six jumps only three were chosen for analysis, the best of each jump type from each subject. Results showed that jumping and releasing weights during flight improved performance by an average of 0.12 m over jumping without weights. It was also found that the best weight for jumping was around 8% of total body weight. Although the results seem to agree with the hypothesis that releasing weights increases distance, there is not enough data to provide statistical significance for the conclusions the study made. In addition, there was no way to tell that the releasing of the weights added any additional performance improvement over simply retaining the weights the entire time throughout the jump since no data was taken for subjects retaining the weights for the entire jump.

In the 2005 study by Huang et al., the subjects retained the weights throughout flight. Nearly identical methods for data capture and analysis were used although this time 12 subjects were tested. The jump types were chosen to be unloaded, light load (2-4 kg), medium load (6-8 kg), and heavy load (10 kg). Each subject performed two jumps for each type of jump with the best one chosen from each type for analysis. The only performance parameter that was chosen for analysis was total jumping distance vs. hand-held weight (in percent body weight). This study showed a lower value for optimum weight at only 6.25% of total body mass as compared to 8% found from the 2003 study. Results of jumping with retaining the weights the entire time and jumping with releasing the weights during flight from the 2003 study cannot be directly compared however, as different subjects were used.

Papadopoulos et al. (2011) performed another study in the area of the standing long jump with weights. Using similar techniques, the study investigated three different jumps: jumping without weights, jumping with 3 kg extra mass, and jumping with 6 kg of extra mass. Results showed an increase of 7 cm for the 3 kg jumps over jumping without weights and a 5 cm increase for the 6 kg jumps. The results are consistent with the Huang study which showed anywhere from a 2 cm – 8 cm increase in performance depending upon weight. This is still far below the optimized jump estimations from the simulations of Minetti and Ardigo (17 cm) and Ashby (39 cm) but consistent enough to indicate that jump performance is indeed improved with hand-held weights. Papadopoulos et al. also showed additional results on ground reaction force and velocity not seen in the Huang study from 2005 to help explain the mechanics that drive this performance increase, citing both joint torque augmentation theory and impart energy theory.

3 Experimental Design

The main performance measure for this study was total jumping distance and how it varied during each jump type. To reduce the amount of variables in the system, the hand-held weight was set as a fixed parameter. No restrictions on takeoff angle were put in place. Subjects were given the freedom to jump to the best of their ability with little instruction other than a demonstration of the desired release points. Based on this scope, five main research questions were proposed.

1) How much does performance improve in the standing long jump when jumping with hand-held weights?
2) Does releasing weights during flight increase jumping distance? If so, by how much?
3) What is the optimal release position of the weights during flight?
4) Do results reflect that of simulation studies?
5) What are the mechanisms that enable performance improvement in the standing long jump when using hand weights?

To address the research questions stated, an experiment was designed to analyze four different jump techniques: without weights, with weights, with weights and releasing them backwards near the high point of the jump, and with weights releasing them backwards just prior to landing. For the rest of the paper, the jump techniques will be referred to as a case as defined in Table 3.1. The two proposed release points in Cases 3 and 4 served as the most logical points in the jump to gain distance as they are the only points during the jump in which the linear velocity of the hands is in the opposite direction to the velocity of the center of mass. An analysis of these four cases will be able to answer not only if releasing the weights during flight increases performance, but also if the release point is significant.

Table 3.1**:** Case Definitions for Each Standing Jump Technique

Case 1	Without weights
Case 2	With weights and not releasing them prior to landing.
Case 3	With weights and releasing them backwards near the high point of the jump
Case 4	With weights and releasing them backwards just prior to landing

The weight chosen for the trials with hand held weights was 5 lb in each hand. This was chosen based on previous studies that found the optimum weight to be around 6% of total body mass (Huang et al., 2005). For a 175 lb male, this results in a total extra weight of 10.5 lbs., or 5.25 lbs. in each hand. Results were rounded to the nearest commercially available weight (5 lb). The chosen weights were roughly cylindrical in shape, fitting easily in the hand and made of a soft bean bag material to reduce risk of injury during the jump (Figure 3.1).

3.1 Subject Selection

Four college male subjects were chosen based on participation in athletic clubs and/or participation in some sort of regular physical activity. The prospective volunteers were asked to take a survey about their physical fitness to determine their level of athletic ability. In order to qualify, the volunteers could not have any persisting back, neck, ankle, knee, hip, shoulder, or elbow injuries and must participate in a physical activity in which jumping is at least mildly involved. Athletic volunteers were preferred since the degree of difficulty in coordinating all the muscle movement during the standing long jump with weight release is high. Better athletes would be able to more consistently perform this maneuver as compared to the average male. The physical properties of the subjects are given in Table 3.2

Table 3.2: Subject physical properties

Subject	Height	Weight (lbs)	Age
1	5’11”	155	21
2	6’3”	207	21
3	6’1”	177	23
4	6’3”	183	22

3.2 Experimental Procedure

Data collection occurred over two different days, separated by three weeks. On each day, before performing the jumps, the subjects went through some simple dynamic warm up procedures. Each subject warmed up by first running on a treadmill for three to five minutes at a comfortable jogging pace (around 6 mph). Subjects were given some leeway on speed and duration as the intent was to warm up the muscles but not introduce any fatigue. The point at which each subject felt adequately warmed up varied based on individual athletic ability. After jogging, the subjects were asked to perform two practice jumps from each case (totaling eight practice jumps). This was intended to familiarize the subject with the motion of the standing long jump and to get a feel for the release points, as these techniques are not common athletic tasks.

After warm-ups, the subjects were asked to perform a total of twelve jumps, three of each case in three separate sets. Each set was ordered following the case order: Case1, Case 2, Case 3, and Case 4. This was done in a repeated manner so that any small fatigue factor would be evenly distributed between the data sets, assuming fatigue factor between cases in a single set is insignificant.

3.2.1 Equipment and Data Collection

Data was captured using a Vicon motion capture system which consisted of eight cameras that record the three dimensional locations of reflective markers placed on the body. The locations of the reflective markers were recorded using the LED strobe lights on each camera operating at 120 Hz. As the subjects moved through the motion capture field the light from the strobes were reflected off the markers attached to the body and back into the camera lens. The Vicon data station recorded the data, and then passed the information to the Nexus system software located on a separate computer where marker labeling and processing occurred.

To capture ground reaction forces and center of pressure location, the subjects jumped off a force plate. This force plate data was needed for calculating many of the performance parameters of the study. The analog data from the force plate was collected at 1440 Hz using the Vicon motion capture system and processed in Nexus in the same manner as the position data.

3.2.2 Marker Selection

Markers were placed on the bony protrusions of the body corresponding to locations close to joint centers (such as elbow, knee, and hip). Bony protrusions also serve to reduce error caused from motion of soft tissue under the skin as there is not much muscle or fat in those locations. The chosen locations were the fifth metatarsal head (toe), the lateral malleolus (ankle), the lateral femoral condyle (knee), the greater trochanter (hip), the acromion (shoulder), the lateral epicondyle of the humerus (elbow), and the ulnar head (wrist). In addition, two reflective markers were placed on either side of the handheld weights. One additional marker was placed on the calcaneus which was used purely for determining take-off and landing times and was excluded from the segment analysis. Example subject marker locations are shown in Figure 3.1.

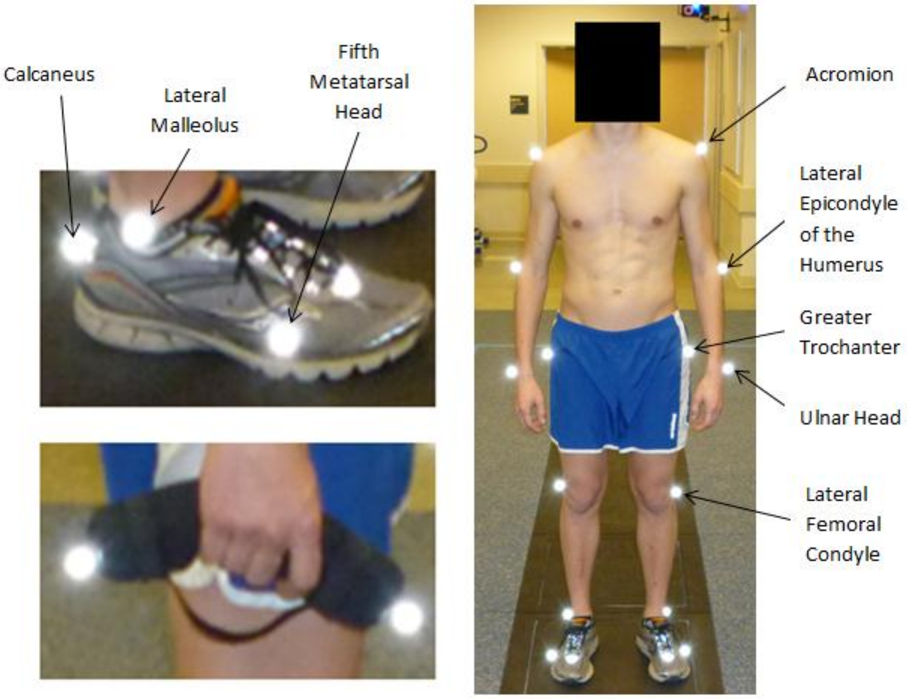

[redacted]

Figure 3.1: Subject Marker Locations

3.2.3 2D Model

The motion of the standing long jump is primarily in a single plane allowing the activity to be modeled in two dimensions. The 2D link segment model formed from the projection of the marker locations onto the sagittal plane is shown in Figure 3.2. Although the subject was marked up on both sides of the body, only the left side was used for the analysis. Body segments and segment angles were then defined from the marker positions as shown in Figure 3.3. Segment angles were defined as positive measuring counter clockwise relative to ground.

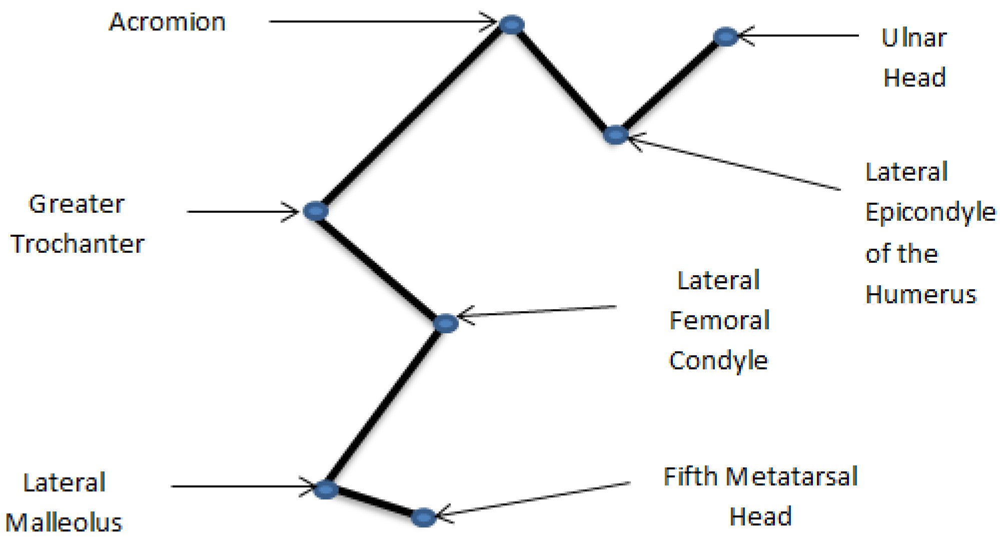


Figure 3.2: 2D Projection Model of Position Markers on the Subject

Joint angles were calculated by subtracting the angle of the distal segment from the angle of the proximal segment. So the ankle for example would be defined as the leg angle minus the foot angle. The only exceptions were the knee and the elbow in which the negative of the angle found from subtracting the segment angles was taken. This was done to define extension (or plantar flexion) as positive in all joints. With this convention, all joint angles besides the ankle were then close to zero when standing upright.

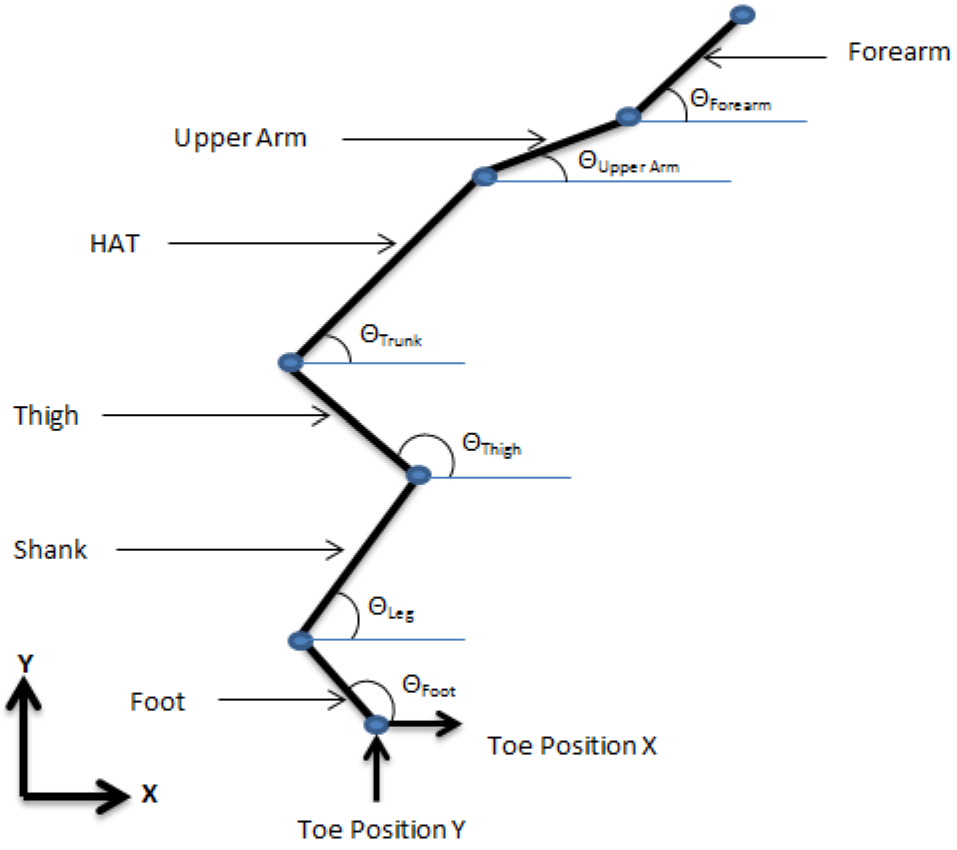


Figure 3.3: Segment Angle Definitions for the Model

4 Data Analysis

Data was analyzed using a combination of Matlab (Mathworks, Natick, MA) and Mathematica (Wolfram Research, Inc., Champaign, IL). The Nexus (Vicon, Los Angeles, CA) software was used to capture and compile the data and output the raw results to be directly uploaded by both Matlab and Mathematica. The first step was to filter the raw data to remove high frequency noise. A bidirectional, 4th order low pass Butterworth filter was applied with a cutoff frequency of 10 Hz for the position marker data and a cutoff frequency of 15 Hz for the force plate data. These frequencies were chosen through an iterative method where a band of frequencies +/- 5 Hz from both values were tested to see their effects on the results. Results showed insignificant changes over this range, validating the choice of cutoff frequencies for the data sets.

Segment properties of mass, inertia, and center of mass were defined according to Winter (2009). Motion independent properties such as segment length and moment of inertia were calculated using static trials to decrease error caused from marker movement during the jump. Segment velocities and accelerations were defined for the centers of mass and calculated using a central finite difference method of the position data.

4.1 Inverse Dynamics Method

An inverse dynamics method was used for computing forces and torques of the body segments outlined in Figure 3.3. Since only the left side markers were analyzed, mass values for the foot, leg, thigh, upper arm and forearm were doubled to account for the right side segments. Each body segment is modeled with internal intersegmental forces and net muscle torque at each joint as shown in Figure 4.1. From this free body diagram, three equations can be defined: sum of forces in the fore-aft (x) direction, sum of forces in the vertical (y) direction, and sum of moments about the center of mass. For the weights, the center of mass was taken to be exactly the average of the two marker locations. The generic forms of these three equations used for every segment are given in Eq. (4.1-4.3).

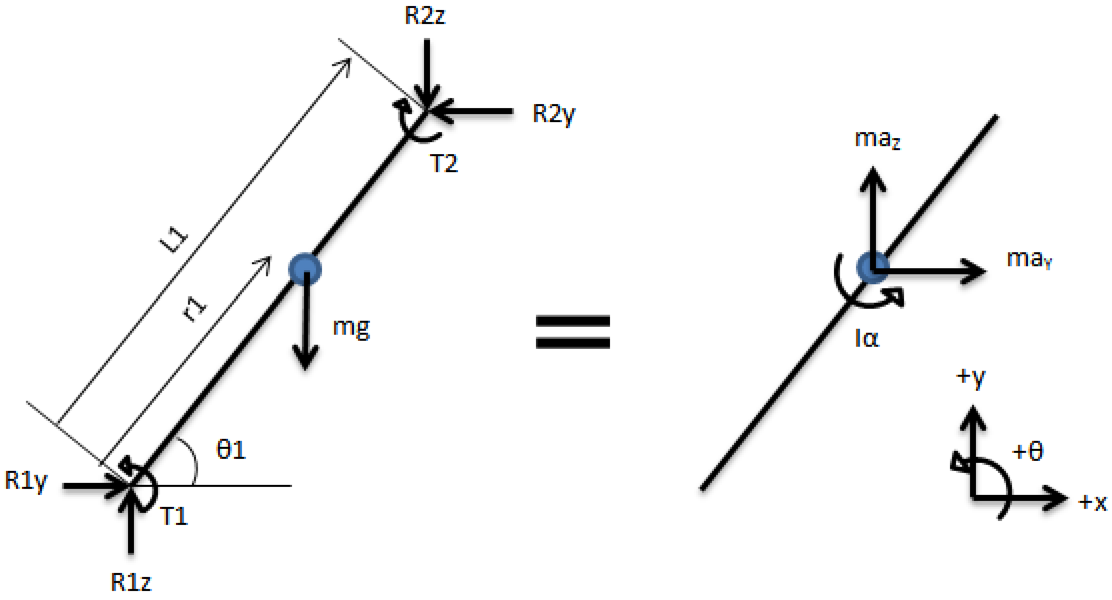


Figure 4.1: Free body diagram used for each body segment set up as a balance of forces

$$\sum F_y = ma_y = R1_y - R2_y \tag{4.1}$$

$$\sum F_z = ma_z = R1_z - R2_z - mg \tag{4.2}$$

$$\sum M_{CG} = I\alpha = T1 - T2 + R1_y[r1 \cdot \sin(\theta 1)] - R1_z[r1 \cdot \cos(\theta 1)]$$
$$+ R1_y[(L1 - r1) \cdot \sin(\theta 1)] - R1_z[(L1 - r1) \cdot \cos(\theta 1)] \tag{4.3}$$

The inverse dynamics analysis method is direction dependent, starting at one end of the body and solving segment by segment using the results from the previous segment. Knowing that the reaction forces and torques at the joints are equal and opposite from that of the previous segment, each new segment is left with three equations and three unknowns. The only segment that is different is the starting segment, in this case the foot, in which the ground reaction forces are known at one end. These ground reaction forces do not occur directly at the joint as in other segments however. They vary along the x-axis according to the location of the center of pressure. Under these conditions, the only unknowns are the intersegmental forces at the ankle and the torque about the ankle. This can be solved using the sum of forces and torques method just like the other segments, providing a starting point to solve all other equations in the system.

Using the inverse dynamics method in this way with known ground reaction forces results in an over constrained system with 15 unknowns and 18 equations. A common method to get results in this kind of system is to throw out the three equations which contain the most error. In a perfect system, the results would remain the same no matter which three equations were thrown out, but that is not realistic for an experimental study. For this study, the ankle through shoulder torques were calculated starting at the foot while the elbow was calculated starting at the wrist. Thus the three equations for the upper arm were not used in this analysis. The elbow was chosen to be calculated from the wrist down in order to fully capture the effects of the hand-held weights. If all torques were calculated starting from the foot, then the largest error would be in the elbow and the only equations that include the hand weights (the forearm equations) would be the three equations not included. Their effect would only be indirectly seen in the motion of the other segments of the body and in the ground reaction forces. Since the main purpose of the study was to see the effect of the weights on performance, it was chosen to keep the forearm equations and throw out the upper arm equations.

After calculating the joint torques, they were then multiplied by angular velocity (calculated using a central differencing of the joint angles) to obtain the net power generated at each joint. Integrating the power curves over time resulted in work done. Analyzing the work between jump types was used to help determine the reasons for differences in jump distance. The total body muscle work was also calculated using an energy balance method by calculating kinetic, potential, and rotational energy at take-off and subtracting it from initial energies of each segment. This method has inherently less error than the inverse dynamics method, but cannot determine the distribution of work done by each joint.

During data collection, it was found that on the first day of study, the force plate output saturated and leveled out during the peak force production, yielding the results unusable. This error was fixed on the second day of the study. Due to this error in the force plate, the inverse dynamic analysis was only done on the data from the second day but the first day data was still used in calculation of the other kinematic performance parameters. The four subjects each performed six jumps of each jump type totaling 24 jumps (12 with force plate data, 12 without).

4.2 Statistics Model

All performance parameters were analyzed using a repeated measures ANOVA model. This model was used to determine significance between jump types, getting a least square mean value for all runs and all subjects within a single jump type. This model is not contaminated by variance between subjects, which is taken into account when calculating significance. The difference between subjects will show up in the mean and confidence intervals but not necessarily in the significance. The total variability in a repeated measures ANOVA is broken up into variance between participants and variance within participants. The variance within participants is further broken down into experimental effect and random error. Figure 4.2 illustrates this breakdown of variance. What is desired is only the variance from the effect of the experiment (SSM). This is the variance that was used for calculation of significance between jump types. The SSR, random error is based on a ratio of how many repeated runs were performed (in this case 6 for each jump type) to the total variance. The more runs performed, the less this effect is seen as it is averaged out over all cases. For the purposes of this study, a threshold p-value of 0.05 was used to indicate statistical significance.

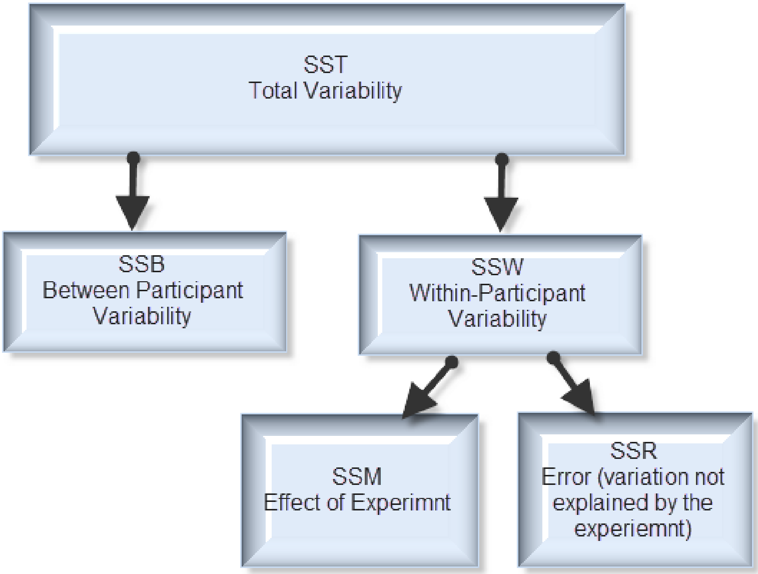


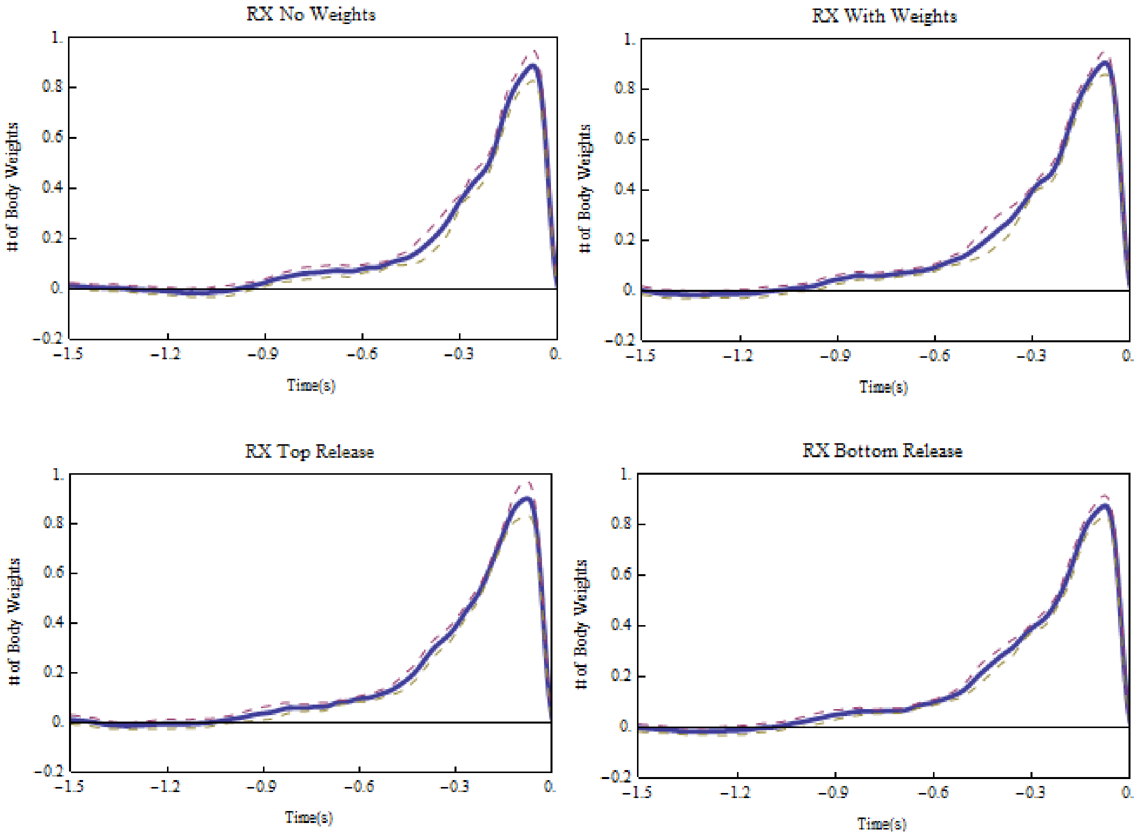
Figure 4.2: Partitioning variance for repeated measures ANOVA (Field, 2009)

5 Results

The main time varying performance parameters (joint torques and reaction forces) were plotted between –1.5 seconds and launch at 0 seconds. These 1.5 seconds are referred to as the propulsive phase of the jump. The length of 1.5 seconds was derived by first determining the point of launch, and scanning back until the ground reaction forces were all about 1.0 body weight. Each subject was allowed to swing his arms for as long as desired to prepare prior to launch and therefore length of time before launch varied for each subject. For analysis, at the very least one arm swing prior to launch needed to be captured. It was determined that 1.5 seconds prior to launch was able to capture this as well as provide similar starting conditions for all subjects.

5.1 Reaction Forces

Reaction forces were normalized to the body weight of each subject to allow for accurate comparison between jump types. Reaction forces are given in Figure 5.1 and Figure 5.2 for the x (fore-aft) and y (vertical) directions, respectively.



RX No Weights

RX With Weights

RX Top Release

RX Bottom Release

Figure 5.1: Fore-aft reaction forces for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

The reaction forces in the fore-aft direction were very similar in all cases, showing very little variation from the mean over time. In all cases, the subjects reached just under one full body weight of force about 0.05 seconds before launch. There is a small dip below zero in the first 0.5 seconds as the subjects swing their arms backwards in preparation for the jump.

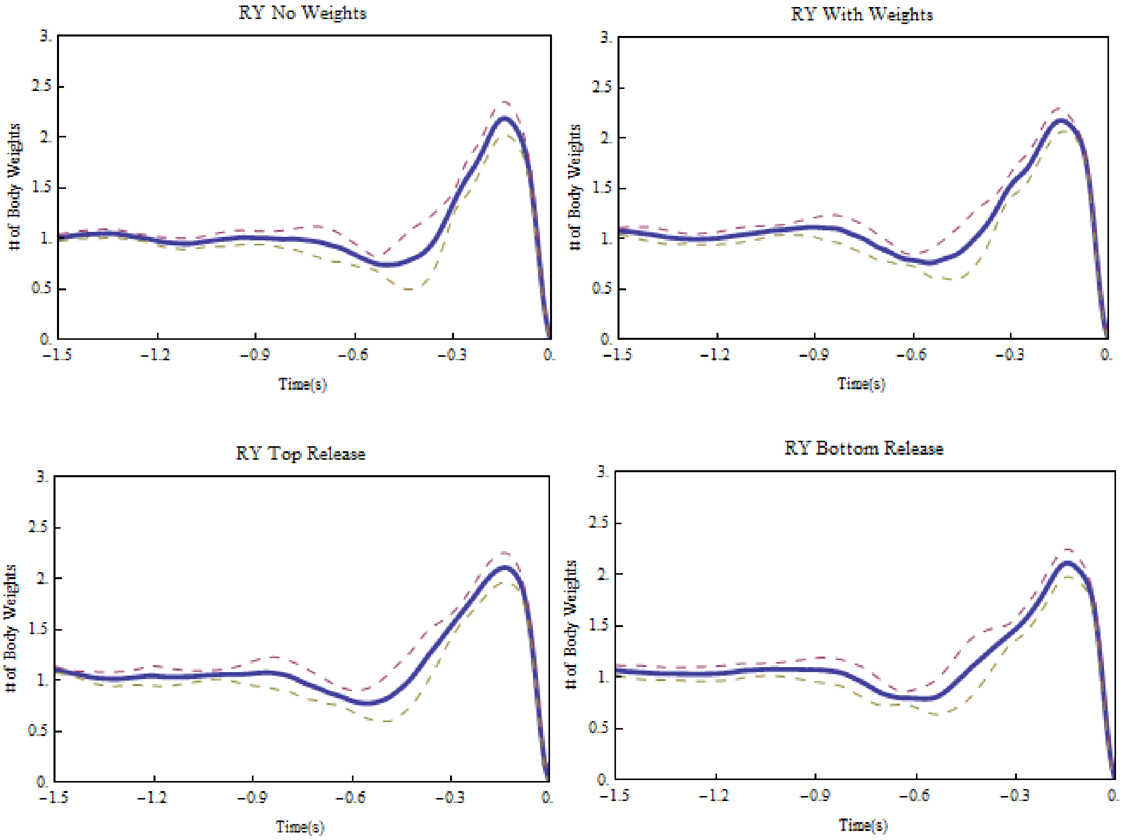


Figure 5.2: Vertical reaction forces for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

The reaction force in the vertical direction also showed similar results for all cases. On average, the subjects produced between 2 and 2.5 body weights of force at peak production occurring at about 0.15 seconds before launch. Some variation can be seen in length of time over which larger forces were produced (the time of the final forward arm swing) between the no weight and with weight cases. It can be seen that in cases with weights, the length of time averaged about 0.5 s where as in the no weight case it only averaged 0.4 s.

5.2 Joint Torques

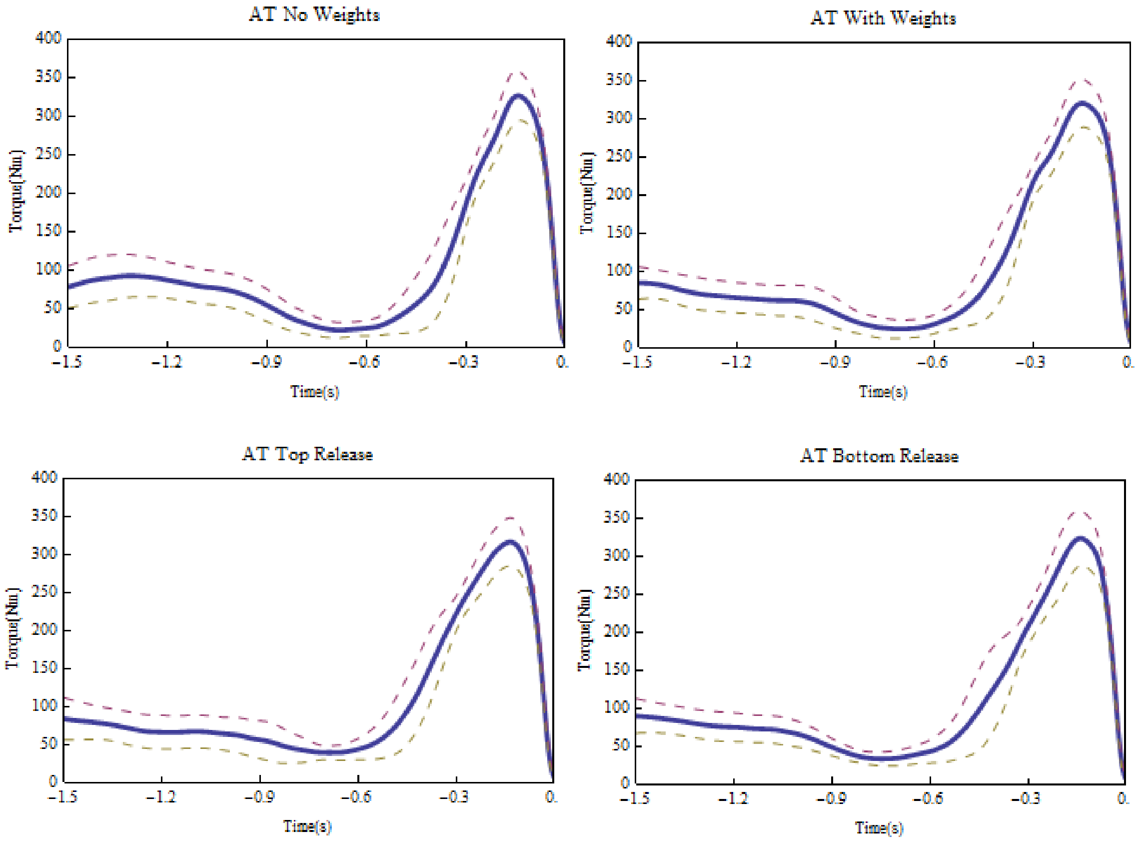


Figure 5.3: Ankle torques for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

Ankle torques show similar results for all cases. Peak force torque was produced at approximately 0.15 seconds before launch, the same time as peak vertical ground reaction force was produced. Torques remained positive throughout the entire jump peaking at approximately 300 Nm. For the first 0.5 seconds (as the arms swing backwards) the ankle applied a positive torque close to 100 Nm.

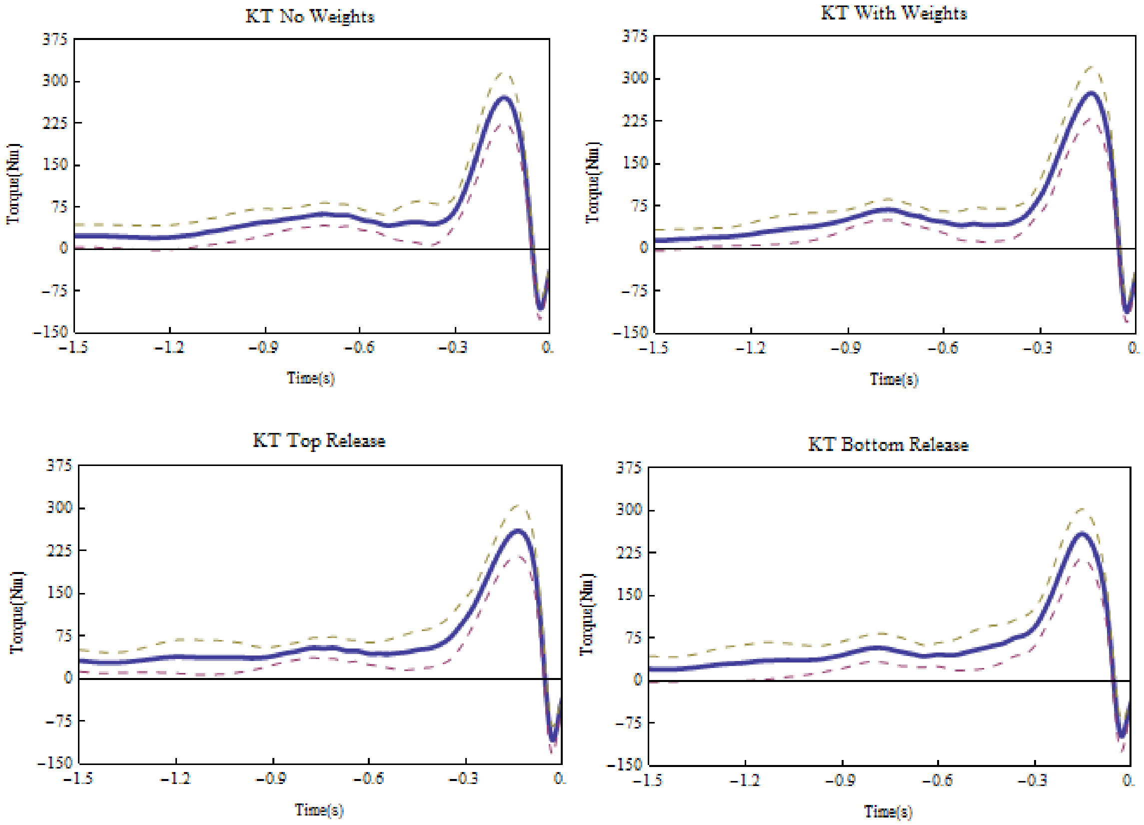


Figure 5.4: Knee torques for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

The knee torques also showed very similar results across all cases. In all cases, there was a characteristic portion of negative torque in the last 0.05 seconds of the jump. Peak torque of just under 300 Nm occurred at 0.15 seconds before launch, same as with the ankle.

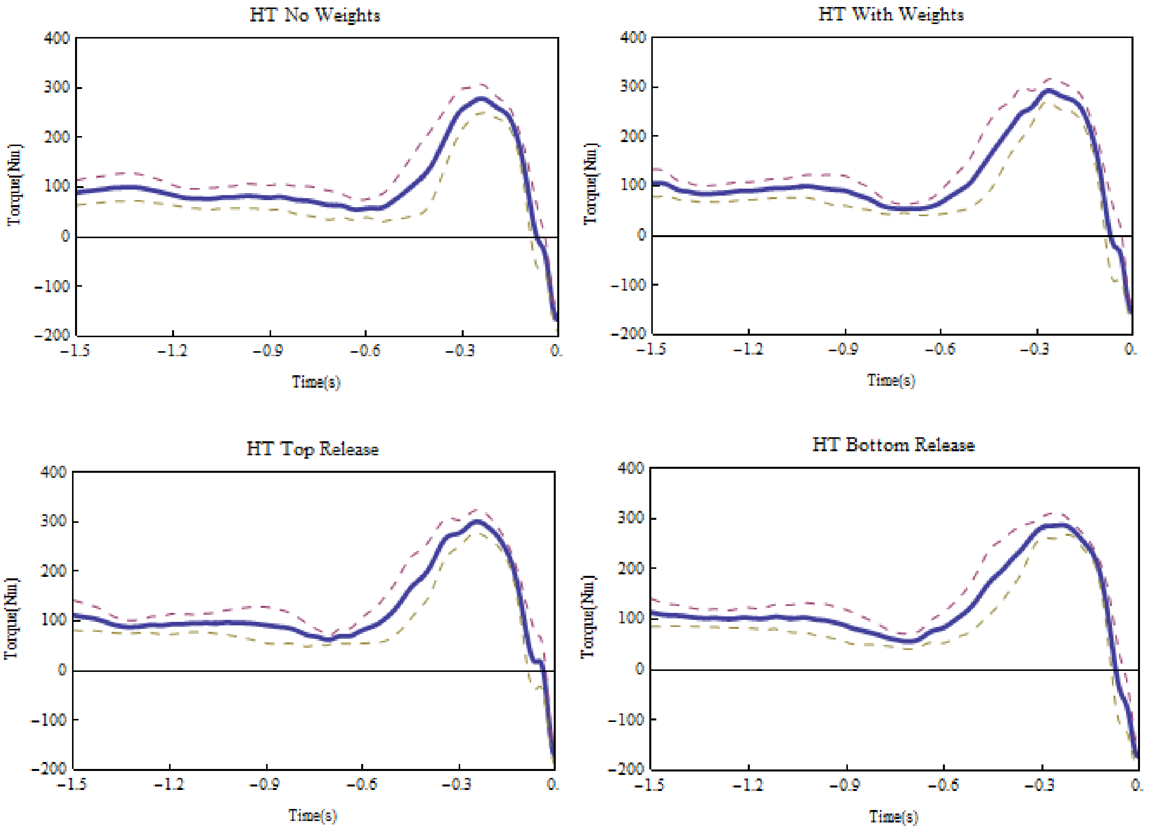


Figure 5.5: Hip torques for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

The hip torques in all cases showed the same negative applied torque in the last 0.05 seconds as was seen in the knee torques. Also the total time of force production during the final arm swing was greater in the with weight cases as was seen in the vertical reaction force curves. Maximum torque of 300 Nm occurred at 0.25 seconds before launch, 0.1 seconds before maximum torque in the knee and ankle.

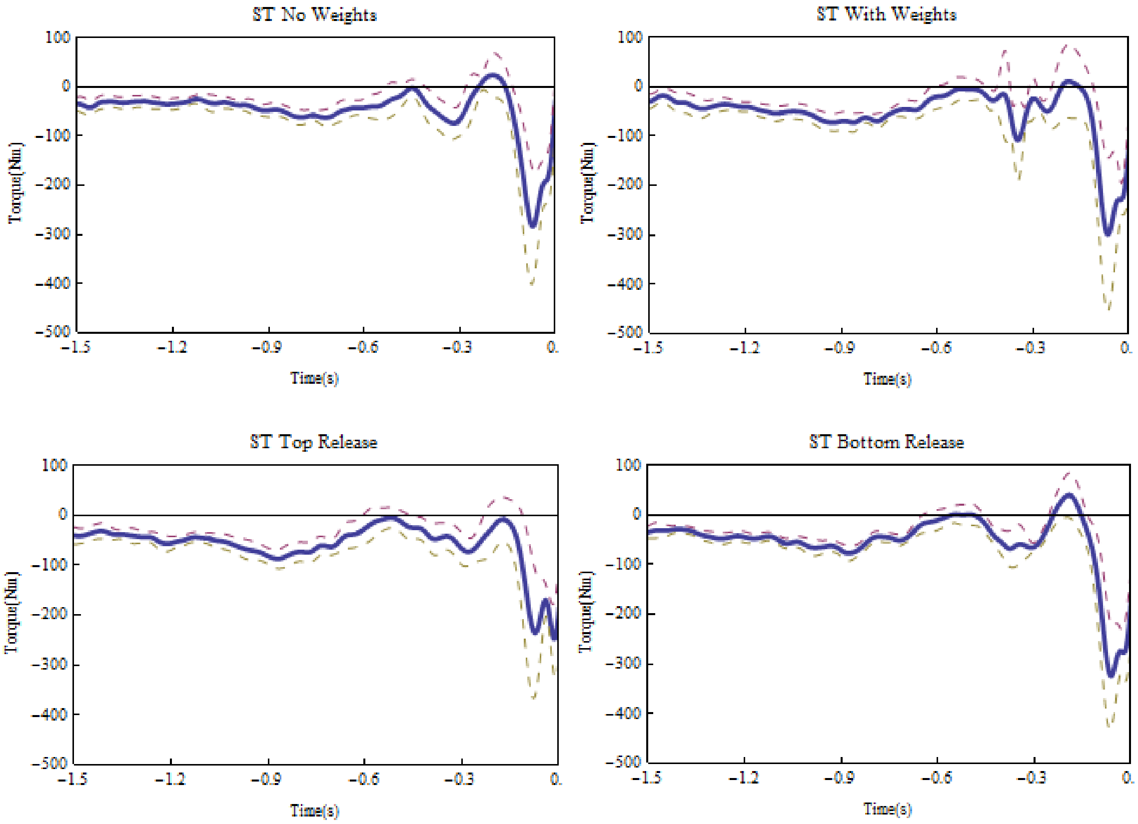


Figure 5.6: Shoulder torques for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

The shoulder torque had larger variations in all cases. Less confidence is given in this calculation. As stated before, any experimental measurement error propagates up the link chain with every segment added in an inverse dynamics analysis. They do all trend in the same direction throughout the jump. Additional uncertainty is added to the calculation from assuming the motion happened purely in the sagittal plane. This was not the case. From observation during data collection, there was a portion (about 0.15 s) during which the arms moved out of the sagittal plane, rotating outward from the body in open arm fly motion. This out-of-plane motion caused calculations of the shoulder and elbow joint angles to be skewed, and therefore ultimately their torque values were skewed as well.

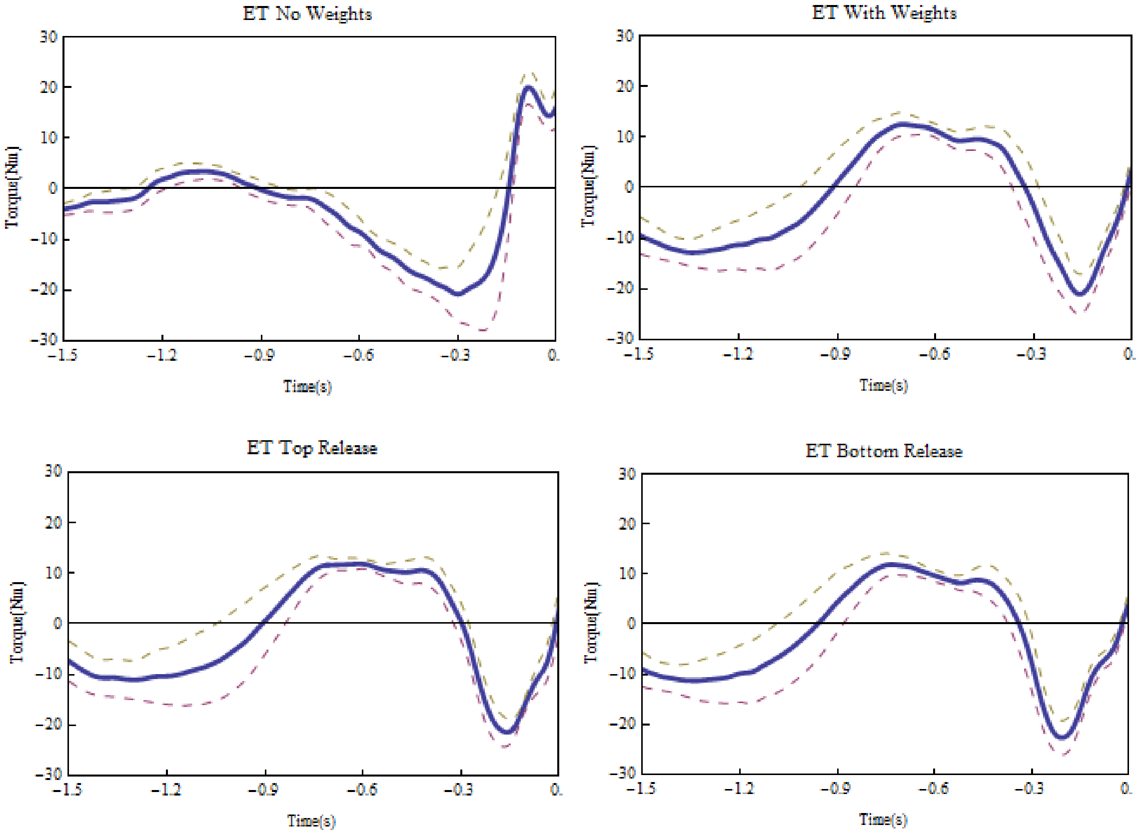


Figure 5.7: Elbow torques for all 4 cases plotted as mean with 95% confidence interval upper and lower limits

The elbow torques were calculated using the equations of motion derived from the forearm segment. These were the only torques calculated from the wrist end of the body and were also the only ones that showed a significant change differences between the no weight and weighted cases. The shape of the elbow torque curve was much different without weights then it was with weights. In the no weight case, the majority of the torque was negative during the final arm swing. The elbow angle and was defined so that extending the arm was positive. Therefore in that negative portion of the jump, the arm was contracting. Towards the end of the arm swing, the elbow extensors contract to extend the elbow generating the small positive torque seen at the end of the jump. For the cases with weights, as the arm swings forward the elbow extends until about 0.3 seconds before launch, at which point the arms contract and generate negative torques for the last portion of the jump.

5.3 Performance Measures

Results for various performance measures are given in Tables 5.1-5.3. The results are displayed as a least squared mean value +/- a 95% confidence interval value. Statistical significance ($p < 0.05$) is given as a superscript above each number by indicating which cases the value differs significantly from. For example if Case 2 was significantly different from Case 1 and 3 but not from Case 4, the number would be reported as $xx.x \pm x.x^{1,3}$.

The total jump distance was the main performance parameter of the experiment. Its result with statistical significance is shown in Table 5.1. Results showed that jumping with weights (Case 2) improved significantly ($p = 0.004$) over no weights (Case 1) by an average of 9 cm. In addition, another 7 cm of improvement ($p = 0.001$) was found from releasing the weights backwards just prior to landing (Case 4). Case 4 was found to be insignificantly greater ($p = 0.104$) from Case 3.

Center of mass velocity and position were also calculated and given in Table 5.1. It was found that velocity in the x-direction was increased using weights without release as compared to no weights ($p = 0.049$), but in the Cases 3 and 4, the velocity in the x-direction showed no statistical difference ($p=0.053$ and $p=0.761$ respectively). The center of mass position increased significantly in the x-direction for all with weight cases (p<0.001 in all cases) as compared to the no weight case. In the y-direction, Case 3 and 4 both increased as compared to Case 1 (p=0.045 and p=0.049 respectively) but only Case 3 increased over Case 2 (p=0.048).

Table 5.1: Key Performance Measures for the 4 Cases

	Case 1 Without Weight	**Case 2 With Weight (No Release)**	**Case 3 With Weight (Top Release)**	**Case 4 With Weight (Bottom Release)**
Jump Distance (m)	2.41 ± 0.06^{2,3,4}	2.50 ± 0.07^{1,4}	2.53 ± 0.07^{1}	2.57 ± 0.07^{1,2}
COM Velocity in x Takeoff (m/s)	3.29 ± 0.10^{2,3}	3.38 ± 0.09^{1,3,4}	3.19 ± 0.08^{2,4}	3.27 ± 0.07^{2,3}
COM Velocity in y Takeoff (m/s)	1.84 ± 0.13	1.82 ± 0.11	1.81 ± 0.09	1.79 ± 0.12
COM Position in x Takeoff (m)	1.41 ± 0.13^{2,3,4}	1.49 ± 0.14^{1}	1.47 ± 0.14^{1}	1.50 ± 0.13^{1}
COM Position in y Takeoff (m)	1.157 ± 0.018^{3,4}	1.162 ± 0.021^{3}	1.176 ± 0.021^{1,2}	1.176 ± 0.026^{1}

From the inverse dynamics method, the work at each joint was calculated and shown in Table 5.2. This method contained a lot of error due to a combination of propagation of error in the system as well as out of plane motion by the arms. Due to the high amount of error, there was a lot of variance between subjects, reducing significance that could be found from the results. No significant differences for the ankle or knee work were found over all cases. For the hip, when compared to Case 1, Case 2 had a significant increase in work done (p = 0.026) but in Cases 3 and 4 showed no significant difference (p=0.760 and p=0.130). Shoulder work did significantly increase in Case 4 compared to all others (p = 0.050 with Case 1, p = 0.015 for Case 2, and p = 0.001 for Case 3). Case 4 also showed the tightest confidence interval for the hip torque as compared to the other three cases. The elbow work showed Case 2 and Case 4 showed no differences (p=0.814) and Case 1 and Case 3 showed no difference (p=0.572). Case 2 and Case 4 produced the least negative work. In terms of total body work, Case 2 and Case 4 were statistically the same (p=0.814) and showed the best results.

Table 5.2: Work done at each joint from the inverse dynamics method

	Case 1 Without Weight	**Case 2 With Weight (No Release)**	**Case 3 With Weight (Top Release)**	**Case 4 With Weight (Bottom Release)**
Work Done at Ankle (J)	226 ± 25	228 ± 26	225 ± 26	236 ± 30
Work Done at Knee (J)	82 ± 37	93 ± 39	86 ± 37	100 ± 42
Work Done at Hip (J)	167 ± 64^{1}	257 ± 82^{1,4}	178 ± 73^{4}	120 ± 63^{2,3}
Work Done at Shoulder (J)	94 ± 38^{4}	64 ± 54^{4}	50 ± 37^{4}	172 ± 59^{1,2,3}
Work Done at Elbow (J)	-16.9 ± 11.5^{2,4}	-1.6 ± 8.3^{1,3}	-10.3 ± 5.1^{2,4}	-1.7 ± 3.8^{1,3}
Total Body Work (J)	553 ± 90^{2}	640 ± 135^{1,3}	528 ± 100^{2,4}	626 ± 85^{3}

The energy analysis results were calculated and shown in Table 5.3. These results could not distinguish which joints contributed to the overall work on the system, but they did provide a more accurate accounting of total work done by all muscles during the propulsive phase of the jump. The results from this energy analysis are reported with more confidence than the joint torque analysis method.

Table 5.3: Energy Analysis

	Case 1 Without Weight	**Case 2 With Weight (No Release)**	**Case 3 With Weight (Top Release)**	**Case 4 With Weight (Bottom Release)**
Translational Kinetic Energy Initial (J)	6.0 ± 3.7^{2,3,4}	14.8 ± 5.9^{1}	18.9 ± 8.0^{1}	17.9 ± 7.2^{1}
Rotational Kinetic Energy Initial (J)	0.57 ± 0.32	0.55 ± 0.19	0.59 ± 0.23	0.59 ± 0.21
Potential Energy Initial (J)	858 ± 40^{2,4}	906 ± 44^{1,3,4}	857 ± 41^{2,4}	887 ± 47^{1,2}
Translational Kinetic Energy Takeoff (J)	635 ± 43^{2}	688 ± 38^{1,3,4}	643 ± 27^{2}	641 ± 33^{2}
Rotational Kinetic Energy Takeoff (J)	18.2 ± 4.1^{3}	19.6 ± 6.8	21.8 ± 4.8^{1,4}	17.4 ± 5.7^{3}
Potential Energy Takeoff (J)	940 ± 47^{2,4}	985 ± 43^{1}	959 ± 48^{4}	997 ± 48^{1,3}
Translational Kinetic Energy Landing (J)	771 ± 103^{3,4}	838 ± 101^{4}	842 ± 97^{1,4}	992 ± 70^{1,2,3}
Rotational Kinetic Energy Landing (J)	48.2 ± 10.8^{3}	46.8 ± 11.3^{3}	37.4 ± 6.7^{1,2}	78.1 ± 53.7
Potential Energy Landing (J)	611 ± 36^{2}	650 ± 41^{1,3}	582 ± 35^{2,4}	627 ± 44^{3}
Total Work Added During Propulsive Phase (J)	694 ± 39^{2,3,4}	770 ± 41^{1}	746 ± 38^{1}	738 ± 49^{1}

Results showed that the cases with weights started out with a significantly higher translational kinetic energy than the no weight case ($p<0.001$ for all). Initially the potential energy for Case 2 was significantly higher than the other cases ($p<0.03$ for all cases), followed by Case 4 ($p=0.007$ over Case 1), with Cases 3 and 1 showing similar potential energy ($p=0.979$). The rotational kinetic energies in all cases were insignificant initially. At takeoff, Case 2 showed the highest translational kinetic energy ($p<0.009$ for all cases), with all other cases showing statistical insignificance compared to each other.

For potential energy at takeoff, Case 2 and Case 4 showed higher values than Case 1 (p=0.001 for both) and Case 3 and 2 showed no statistical differences (p=0.156). Rotational kinetic energy was highest for Case 3 (p=0.038 for Case 1 and p=0.021 for Case 4), but compared to the magnitude of the translational kinetic and potential energy at take-off, the rotational kinetic energy was not a substantial contributor to the overall energy in the system.

For the energy analysis at landing, the results should mimic the results at takeoff as energy is conserved and no external force acts upon the system. The only difference being that in the weight release cases, the translational kinetic and potential energy at landing were calculated for only the center of the mass of the body excluding the weights. It was observed that the translational kinetic energy at landing for Case 4 was significantly higher than the other cases (p=0.001 for Case 1, p=0.004 for Case 2, p=0.005 for Case 3), indicating that the body was able to increase its energy by releasing the weights backwards during flight. The total energy of the system including the weights remained the same, but just the body portion was propelled forward as the weights moved backward. Overall, the work added to the system in the cases with weights was higher than the no weight case (p=0.001 for Case 2, p=0.033 for Case 3 and p=0.030 for Case 4).

6 Discussion

Jumping with weights changed many of the mechanics throughout the jumping motion. First off, when jumping with weights and not releasing them, the subjects were able to generate more kinetic and potential energy at takeoff as compared to the no weight case. This was due in part from the higher kinetic energy at the initiation of the jump as well as the added potential energy stored in the weights at initiation. This resulted in an increase in the center of mass velocity and center of mass position at takeoff in the horizontal direction. The added mass of the weights also slowed down the time it took for the final arm swing, as shown by the vertical ground reaction forces, allowing the body to generate more energy. On average, with weights, the final arm swing took 0.1 seconds longer generating around 80 J more energy than without weights. This matches previous literature findings that the use of hand weights slows the motion of the body during the preparatory countermovement of the jump allowing the body to do more work (Nagano, 2008; Felter, 1999).

Case 3 further changed the mechanics of the jump through releasing the weights backwards at the highest point of the jump. When compared to jumping with weights and no release, it was found that statistically, the energy produced during the propulsive phase was near the same, but less of it was in the form of kinetic energy at takeoff. This resulted in a slower horizontal takeoff velocity (lowered by 0.19 m/s). This was suspected to be caused by the subjects holding back during the propulsive phase due to concerns about executing the release point properly. This has been seen in the literature for other jumping techniques such as when subjects jump without using any arm motion (Ashby and Heegaard, 2002). Although this is not the same maneuver as jumping without arm motion, the same principles of holding back to maintain balance and stability still apply. Even though the velocity at takeoff was lower, the subjects still saw an improvement in jump distance. Since it did not happen during the propulsive phase, it must have occurred due to the principles of conservation of linear momentum in the flight phase of the jump. When the subjects released the weights backwards, the rest of the body would have to move forward in order for the center of mass of the whole system to remain in the same path. Had the same amount of energy been generated as in Case 2 and the weights had been released at the same position, even further distance over the 3 cm could have been gained. Further research might look into training the subjects so they have confidence in the mechanics of the release point and would not hold back during the propulsive phase of the jump.

Case 4 statistically showed no difference in jump performance as compared to Case 3 and yielded similar improvement in results when compared to Case 2. There was a lower kinetic energy and horizontal center of mass velocity at takeoff compared to Case 2, similar to what was found between Case 3 and 2. Case 4 did however show a much higher level of work at the shoulder (108 J more than Case 2 and 122 J more than Case 3). While less confidence is given in the actual number values due to the error propagation in the inverse dynamics method, this high of an increase suggests there is a significant difference in the jumping method. From observation, it was seen that the subjects did not raise their arms as high in Case 4 as compared to all other cases. This was most likely so the subjects could bring the arms backwards faster in the flight phase and therefore release the weights earlier gaining more distance (again due to the laws of conservation of linear momentum). Not bringing them as high means the arms did not need to waste energy to increase the potential energy of the weights and instead the energy could be transmitted elsewhere in the body.

When looking at the torque production of each joint, it was found that only the hip shoulder and elbow differed significantly between cases. The ankle and knee had no significant differences in findings for all 4 cases. For the ankle, this makes sense because the foot remains stationary for the majority of the preparatory phase of the jump. This also matches findings from the literature where the ankle had little effect on performance with weights (Feltner, 1999). The differences in the shoulder work in cases with weights and the associated increase on work done by the lower body segments suggests evidence that joint torque augmentation played a factor in the improvement of jump performance. It was not seen conclusively in all cases but Case 2 definitely saw an increase in work done by the lower body segments as compared to Case 1 without weights. A more definitive explanation to the increase in work would be the impart energy theory or pull theory as talked about in the literature (Ashby and Delp, 2005; Lees et. al., 2004; Papadopoulos, 2011). Extra energy stored in the weights (both kinetic and potential) in the initiation phase was seen for all cases with weights. This extra energy from the weights was successfully transferred to an increase in kinetic energy at takeoff for Case 2, but not as effectively in Cases 3 or Case 4. This was suspected to be due to the subjects holding back during the propulsive phase as discussed before. The fact that the overall energy added during the propulsive phase significantly increased in all cases with weights compared to no weights suggest impart energy theory played a factor, but the level of improvement that was gained was dictated in each case by the amount of hold back applied by the subject.

In all of the cases, the knee torques and hip torques showed a characteristic negative dip in the last 0.05 seconds before takeoff. It is possible that the subjects applied these negative torques just prior to launch to prevent hyperextension of the joints or to maintain balance and prevent a toppling moment about the center of mass. This inefficiency in total torque production is not ideal for jumping but might be a factor of the subjects not being that experienced in the performance of the standing long jump. With training, the subjects might be able to remove this inefficiency and improve performance.

To address the research questions proposed by this study, for number 1, it was proven that jumping with weights increased performance. This was seen not only in the distance gained but also in the work done before takeoff. For number 2, it was proven that releasing the weights further improved performance over Case 2 by an additional 3 cm for Case 3 and 7 cm for Case 4. When compared to Case 1, Case 3 and Case 4 improved by 12 cm and 16 cm respectively. This shows comparable results to earlier studies findings for weight release jumps (Huang, 2003) which found an average of about 12 cm of improvement from releasing the weights backwards at the top of the jump. For number 3, statistically speaking, the release point had no effect on jumping performance; therefore both methods of release will yield the same net improvement. From observation and talking with the subjects however, most agreed that the bottom release method was easier and they felt they performed better and the results were fairly close between the two cases ($p=0.104$). Further studies with trained athletes might be able to find better significance between the two but it was not seen in this study.

When compared to previous simulation studies (Ashby, 2005; Minetti and Ardigo, 2002), the results of an increase in 3-7 cm from releasing the weights compared to no release only partially validated their results. In the simulation study by Ashby, it was hypothesized that the release point at the top of the jump would derive the most performance improvement. The experimental results did not reflect this. If anything the bottom release point had a slightly higher mean, although the difference was not statistically significant. This could be a factor of the subjects not executing the release points the same as in the simulations, or the simulations did not contain all the same parameters experienced by the subjects during the experimental trial. Training the subjects on the proper release method could bring the results closer to the simulation results. For the last research question about the mechanisms that enabled performance improvement, most have been discussed already. They include an increase in work done by the body prior to takeoff due to the joint torque augmentation theory, an increase in center of mass position in the horizontal direction at takeoff, and an increase in velocity of the body in flight gained from conservation of linear momentum when the weights were released.

Obtaining reliable results for joint torques with the inverse dynamics method is a well-established challenge. There are a number of other potential methods for performing inverse dynamics that could be explored. For example, better results might be obtained by finding the least squares solution using all 18 equations. In this study, the results from the energy analysis were found to be much more significant than the results from the inverse dynamics method. This is to be expected based on the error propagation through each successive segment. Future research might want to look into better methods for analyzing the inverse dynamics equations, such as the least mean square method.

7 Conclusions

Performance in the standing long jump was compared between four jumping techniques: no weights, with weights, with weights released backwards at the highest point in the jump, and with weights released backwards just prior to landing. Jump distance was found to be improved by jumping with weights over jumping without by an average of 9 cm. In addition, releasing those weights just before landing added an additional 3-7 cm of distance on average. From this analysis, release point was not found to be a significant factor on the level of performance improvement. The results partially validate simulation studies done (Ashby, 2005; Minetti and Ardigo, 2002) in that releasing weights during flight did increase jump distance, however, the results were unable to statistically find one release point to be better than the other as seen in the simulations. This could have been a factor of the subjects not receiving training on how to execute the release points properly. The increase in jump distance with weights was attributed to an increase of an average of 50 J of work done by the body during the propulsive phase of the jump and an increase in horizontal takeoff position. Additional distance was gained in flight from releasing the weights due to conservation of linear momentum. This can be seen by looking at an increase in the combination of kinetic and potential energy at landing as compared to the no weight case and the case with no release point. Overall, it was proven that it is possible to increase performance in the standing long jump by releasing the weights

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