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Jump Distance Increases While Carrying Handheld Weights: Impulse, History, and Jump Performance in a Simple Lab Exercise

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This laboratory exercise is designed to provide an understanding of the mechanical concept of impulse as it applies to human movement and athletic performance. Students compare jumps performed with and without handheld weights. Contrary to initial expectation, jump distance is increased with moderate additional weights. This was familiar to Ancient Greek athletes where "halteres" were a part of the original Olympic jumping sports. The effectiveness of this laboratory was assessed with a prelab questionnaire evaluating understanding of the concepts relevant to jumping mechanics and a postlab questionnaire assessing understanding of the same principles in the context of a different but mechanically analogous circumstance, that of throwing. Results indicate that understanding improved significantly as a result of participation in the laboratory exercise.

KEY WORDS: impulse; jump; halteres; acceleration.

INTRODUCTION

Any human movement results from a complex interaction between the individual and the physical world. An understanding of the principles of physics is fundamental to understanding the complexities of movement. Particularly fundamental is the concept of impulse, the product of force and time over which force is applied, which is itself responsible for the momentum changes that result in motions such as jumps. It is only within the context of understanding the influence of fundamental physical interactions that students of human function and performance can assess the role of the physiologically determined factors of the neuromuscular and the musculoskeletal systems in an activity like jumping.

Examples of the influence of physics principles occur in all activities, even though they may seem obscure to students unfamiliar with those principles or their application. Students can be drawn into applying, and consequently understanding, these principles if they are stimulated by witnessing an unexpected phenomenon. This is the motivation for the experiment that forms the basis of this study. We have formulated an easily reproduced low technology experiment that will demonstrate that carrying handheld weights can increase jump distance.

Carrying any extra weight while jumping certainly seems counterproductive. One could reason that an increase in overall body weight must decrease jumping distance due to the extra weight that must be accelerated off the ground. If the muscles are responsible for that acceleration, and if those muscles function maximally in unloaded conditions to produce a maximal jump, then an additional load must decrease performance. This seeming paradox makes the use of handheld weights in jumping an engaging laboratory experience for students. It challenges their initial understanding of jumping and their notions of what influences jump performance.

Handheld weights, also known as halteres, can increase jump distance for several well-defined reasons (Minetti and Ardigó, 2002; see a full explanation

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below in the sectionhead Biomechanics of Jumping). By witnessing a phenomenon that is opposite to their expectations, students are driven to seek an explanation. That explanation requires an understanding of the key mechanical concept of impulse.

Jumping sports, both running long jump and high jump, were included in the pentathlon, a popular competition of the original Olympic games nearly 3000 years ago (~700 B.C.) (Gardiner, 1930; Tasch, 1952). Interestingly, the ancient athletes carried handheld halteres while jumping. Halteres were most commonly made of stone (Tasch, 1952) and ranged in weight between 2 and 9 kg (Minetti and Ardigó, 2002). Stone halteres were typically hemispherical with either rounded or pointed ends and a recessed or pierced upper edge to allow gripping (Gardiner, 1930), much like a primitive form of a modern dumbbell.

The motivation for the use of halteres came, of course, from the fact that measurable increases in jump distance result from their use, even if the ancient Greeks had no formal understanding of why (Tasch, 1952). Some claims have suggested early Olympians were capable of remarkable jumps. For example, archaeological evidence indicates that ancient Greek sport jumping pits, known as “skamma,” were built up to approximately 15 m in length. Written legends of the time tell of athletes with individual long jumps exceeding the length of the skamma (Gardiner, 1930; Harris, 1966). For perspective, the current world record for the long jump is approximately 8.95 m (Ward-Smith, 1995). It is quite improbable that jumps anywhere near this length were actually made, but often legend has a basis in some form of fact. These athletes did do extensive practicing in this event, sometimes even to the accompaniment of flute musicians to assist in the timing of their technique (Gardiner, 1930; Harris, 1966). This lab exercise uses a simple study to investigate the effect of carrying handheld weights while jumping and is designed to provide the modern exercise science student with the understanding of the physics of jumping that was unavailable to the ancient Greeks.

The Experiment

Overview

The experiment involves the determination of jump distance, comparing standing long jumps with and without handheld weights. A standing jump is chosen over running because it is better controlled, involves less chance of injury and requires substantially less space. The long jump is chosen over the high jump because it is more readily measured in a lab setting. A range of hand weights is used to evaluate whether jumping distance is sensitive to the magnitude of carried weight. Jump distances for each pair of weights carried are measured and these data are compared to the jump distance of the same subject without handheld weights. The following is a description of the experiment with some suggestions for effectively managing the exercise.

Setup

The experiment works best if students work in small groups. A larger, open space should be used, such as a gymnasium, hallway, or room cleared of furniture. We have found that five is the most effective group for conducting jump trials. A group of 5 provides a role for each student while allowing the experiment to be conducted safely: two students from each group serve as subjects, two students mark and measure the length of each jump, while one student serves as data recorder. Jumps should begin from a recognizable point such as a strip of colored tape placed on the floor. The distance of each jump is “spotted” by eye and measured from the starting line using a tape measure.

Standard solid dumbbells work well for the handheld weights. These are inexpensive and readily available at sporting goods stores. Adjustable weights should be avoided simply because there is some chance that the collars holding the weights in place could come lose during the jumps. For college-level students we have had success using pairs of 1.4-, 2.3-, and 3.6-kg dumbbells. We have several dumbbell pairs of each mass available when conducting the experiment to facilitate multiple groups completing the lab in a minimum time.

Safety Concerns

Dumbbells of 3.6 kg or more can become quite cumbersome, especially for smaller subjects. The issue of safety is essential for both the jumpers and the students taking measurements. Upper body muscles and connective tissue injuries are possible in this exercise. Our experience is that vigilant monitoring of students while they perform the jumps combined with prelab cautions and warm-ups by the jumpers have limited injuries to only mild muscle soreness that follows any unaccustomed activity.

Students carrying dumbbell weights while jumping must be careful to avoid slips. The floor surface should provide suitable friction. Harder surfaces should be dustfree and it is important to test the interaction between floor and shoe of the jumper with some submaximal test jumps. Additionally, students should clean the external soles of their shoes with a standard cleaning solution to remove any excess dirt and dust before performing jumps.

Of greatest safety concern is avoiding an accidental knock by the weight. It is possible for an overexuberant jumper to lose control of the weight and knock themselves, either in a normal jump, or more likely if they partially lose stability on landing and try to compensate with arm movements. It is also possible for an overexuberant student taking the distance measurements to rush in to the landing mark and become vulnerable to a swinging weight before the jumper has come to a complete stop. Likewise, students in the vicinity of takeoff (whether in the jumper's group or not) need to be mindful of the arc traversed by the weights as they are swung backward and forward for the jump. Students may also accidentally release the weights in the process of swinging their arms upwards at takeoff or while flying through the air. Prior to running this experiment jumpers need to be cautioned to avoid this and other members of the group must be aware that it is their responsibility to stay out of the way of the trajectory should something unforeseen occur.

Jumping Trials

A minimum of two students from each group should perform a series of standing long jumps, alternately with and without dumbbell weights. A more thorough analysis can be accomplished by including more subjects if lab time permits, but the results should be clear even with two subjects from a group.

Subjects will initially jump without carrying weights. Jumps made without weights will serve as controls and have the added function of preparing the subject for the more rigorous weighted jumps. Subsequently, subjects will jump carrying pairs of 1.4-, 2.3-, or 3.6-kg dumbbells. Jumps made with dumbbells are the treatment trials. A total of 12 measured jumps are performed by each subject: 3 jumps with no weights and 3 jumps carrying each of the dumbbell weight pairs (see Appendix A for a sample data sheet).

Three replicates per trial condition are recommended so that an average jump distance can be reliably determined. However, jumps for a given trial condition should not be performed consecutively. With the limited time for practice available in the lab setting, it is possible that some type of "training effect" can occur as the subject becomes more familiar with jumping, or becomes more at ease jumping with the weights in hand. If treatment differences are coincident with a training effect, then this may obscure the effects of the added masses. The study requires a sampling strategy that minimizes the influence of this effect. Any method of varying the sequence of jump treatments is suitable. We have had success simply cycling through the single jumps beginning with unweighted through 1.4-, 2.3-, and 3.6-kg masses and repeating until the desired three replicates of each are complete (Appendix A). This reduces the influence of training effects on any single treatment trial while providing a gradient of load levels so that the subject is not faced with a large difference in jumping conditions between successive trials.

Finally, it is quite prudent to allow the subjects to make at least a few practice jumps prior to the initiation of the experiment, or prior to the measurement jump under each of the treatment trial conditions, provided these are not so numerous that the subject becomes fatigued. Although everyone who jumps employs arm motion, doing so effectively with weights in hand requires some practice.

Data Analysis

Once all jump distance measurements are complete (three trials each at three weight levels and the control, for each of the two subjects per group), the average jumping distance for the control and treatment trial jumps can be computed. These averages represent the mean absolute jump distance for each subject under each trial condition. Alternatively, the best jump from each of the three trials can be used to represent the maximal capability of the jumper. We prefer the average because it provides students with experience considering the effect of multiple jumps.

Within each subject the computed average will indicate the effect of the added mass. However, it will be difficult to compare performance between individuals unless all subjects are uniform in height, weight, and jumping ability. This is because height and weight affect absolute jump performance and, as a result, the apparent influence of the different haltere masses. This "size" effect will be a large portion of the unexplained variability of the data unless it is properly accounted for.

An appropriate analysis would examine the normalized (relative or proportional) changes (Hof, 1996) in jump distance. We offer three forms of normalization that will account for much of the (1) length, (2) body weight, and (3) athletic differences between subjects. Jump distance can be normalized by dividing each subject's mean absolute jump distance (for both the control and treatment jumping trials) by a standard length that characterizes the individual, e.g., body height or leg length (Ford, 1984). We suggest using leg length (distance from floor to lateral point of the greater trochanter, an easily identified, consistent anatomical landmark). Normalized jump distance is given as a proportion (or percentage) of the subject's leg length. Similarly, the mass carried should be normalized to the subject's body mass. Normalized mass carried is calculated by dividing a subject's body mass into the total mass (both dumbbells) carried while jumping. Normalized mass carried for the control jumping trials is 0%. One benefit of normalizing all data is the reduction of variability both between and within subjects (Pierrynowski and Galea, 2001).

Through normalization the influences of covariables such as subject height and mass are removed (Moisio *et al.*, 2003) and changes in jump distance can be readily discerned. However, comparisons between subjects may also be obscured by a large difference in innate jumping ability. Even in size normalized comparisons, substantial differences may occur between jumpers. The influence of the carried mass on jumping ability of each subject can best be seen by comparing the *change* in normalized jump distance.

Lab Exercise Results

This experiment consistently yields results indicating that jumping with handheld mass can increase jump distance (Fig. 1). A functional limitation of handheld mass improvements is also indicated in the example data. Even though moderate masses increase jump distance for both subjects, further increases will eventually inhibit jump performance. Jump distance of Subject A increases even with 3.6 kg (Table I). As a much larger individual, the 3.6-kg halteres totaled only 8% of Subject A's body mass, whereas they were nearly 13% of Subject B's (Fig. 1; Table I). Note that a plot of the change in normalized jump distance against carried mass (as a percentage of body mass) indicates that the effect of the halteres on each of these jumpers is very similar (Fig. 1), but the larger individual (A)

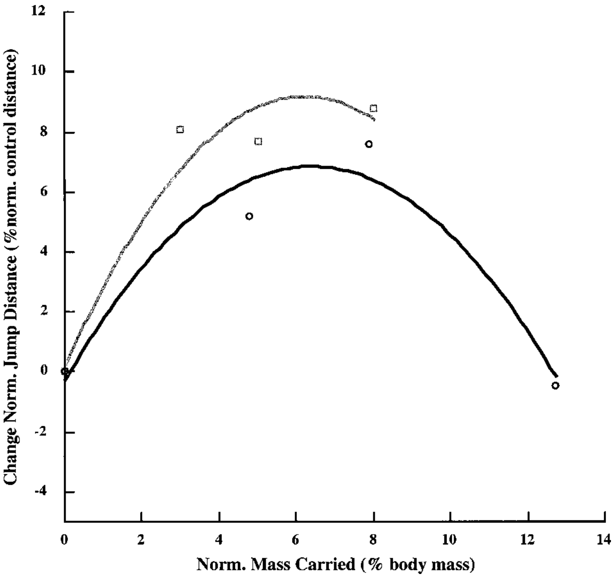

Fig. 1. Jump distance data for two jumping subjects. The change in normalized jump distance (expressed as a percentage of normalized control jump distance) more clearly shows the trend of increased jump distance by the addition of handheld weights. Curves are 2nd-order polynomial regressions. Compared with the controls (0% normalized mass carried), jump distance generally increased for both subjects with some additional amount of mass carried in the hands. Subject B (black curve; open circles) showed a decrease in jump performance for jumps made with the 3.6-kg hatteres while jump performance for Subject A (gray curve; open squares) was proportionately greater (≅9%) than normalized control jump distance on jumps made with the 3.6-kg halteres.

Table I. Student Data for Standing Long Jumps Made With a Range of Handheld Dumbbell Weights

Mass carried (kg)	Jump distance (m)	Norm. mass carried (% bw)	Norm. distance (prop. leg length)
Subject A[a]			
0	2.81 ± 0.044	0	2.73
1.4	3.04 ± 0.104	3.0	2.95
2.3	3.03 ± 0.080	5.0	2.94
3.6	3.06 ± 0.065	8.0	2.97
Subject B[b]			
0	1.98 ± 0.023	0	2.11
1.4	2.08 ± 0.081	4.8	2.22
2.3	2.14 ± 0.031	7.9	2.27
3.6	1.97 ± 0.035	12.7	2.10

Note. Jump distance is given as $M \pm$ SD for three jumps made with each of the specified masses carried.

[a] Male: 90.9 kg; leg length, 1.03 m.

[b] Female: 57.3 kg; leg length, 0.94 m.

was not loaded equivalently to B. However, extrapolation of this relation would predict that the jump distance of Subject A would also be decreased at haltere masses summing to 13% of this individual's body mass.

Once the student groups have demonstrated the unexpected influence of handheld weights on jumping performance, it is our experience that they will be anxious to understand why this occurs. Following completion of the analysis the explanation supplied below (Biomechanics of Jumping) is well received and generates numerous questions.

Learning Assessment

This laboratory experience is designed to emphasize the important influence of impulse on human motion. By using the application of concepts such as impulse in jumping with handheld weights the students become engaged with the physics principles involved. Most students will have a basic understanding of jumping prior to the laboratory experiment. However, unless specifically taught such concepts, they will likely not be able to apply these principles appropriately. The effectiveness of this laboratory as a teaching tool is evaluated by measuring the understanding of participating students (1) prior to the laboratory by asking questions directly related to jumping, (2) after the laboratory using the same assessment tool, and (3) after the lab using an analogous assessment tool that questions the same concepts, but in a different context.

Initial understanding of motion was assessed using a "prelab"questionnaire (Pre 1). This was composed of 10 general questions on the mechanics involved with jumping. The prelab questionnaire was administered several days in advance of the lab exercise. Questions were formatted as open statements and students were required to choose between two alternative answers to make each open statement true. Scoring assigned a value of 1 for a correct response and 0 for an incorrect response.

Several days following the laboratory experiment the prelab questionnaire was readministered (Pre 2). This was done to determine student's final level of understanding of jumping mechanics. As well, a second, "postlab" questionnaire (Post) was administered. The postlab questionnaire was organized to be similar in conceptual content to Pre 1 but the questions involved the mechanics of throwing (see Appendix B for samples of both the prelab and postlab questionnaires). Throwing was selected as the focus of this questionnaire because its understanding requires the use of the same concepts as jumping, but it is an activity that in many ways can be considered the inverse of jumping; a projectile is accelerated away from the body rather the body accelerated as a projectile. By forming the second evaluation in the context of an activity that was not directly related to the specifics of the material covered by the lab exercise, it was assumed that the assessment would be a superior evaluation of how well the concepts of the lab were assimilated and could be synthesized by the students.

Totals for the number of correct responses for each question per questionnaire were determined and summed. The means of the total number of correct responses/questionnaire were then compared using a paired Student's t test (Statview, SAS Institute, Cary, NC) to determine significant differences between the pre- and postexperiment conditions. Significance was accepted at $p \leq 0.05$. A significant difference in the positive direction was interpreted as a measure of the effectiveness of the laboratory exercise in improving students' understanding of the fundamental principles involved in motion.

Assessment Results

Out of a possible 10, the mean number of correct responses on the Pre 1 questionnaire was 5.40 ± 1.59 (±SD, $n = 60$; Table II). Since each question only allowed the selection of two options as answers, random selection is expected to result in a score of 5. The class result was not significantly different from random and demonstrates a fundamental misunderstanding of the physics of jumping within these students. Following the lab experiment, mean number of correct responses on the Pre 2 questionnaire improved significantly to 7.47 ± 1.57 ($p < 0.001$ paired Student's t test; Table II). Similarly, a comparison of means of number of correct responses between Pre 1

Table II. Means ± SD of Total Number of Correct Response on Each of the Learning Assessment Questionnaires

Questionnaire	Number of respondents	Total correct responses	p
Pre 1	60	5.40 ± 1.59	
Pre 2	59	7.47 ± 1.57	0.1628
Post	58	7.07 ± 1.84*	

*$p < 0.0001$ (significantly different from Pre 1 by a paired Student's *t* test).

Table III. Proportion of Correct Responses to Individual Questions on Each of the Learning Assessment Questionnaires

Question #	1	2	3	4	5	6	7	8	9	10
Pre 1	0.65	0.42	0.20	0.85	0.97	0.70	0.17	0.22	0.72	0.55
Pre 2	0.83	0.81	0.42	0.97	1.0	0.85	0.41	0.80	0.85	0.54
Post	0.69	0.67	0.38	0.74	0.90	0.79	0.53	0.91	0.78	0.67

questionnaire and Post questionnaire also resulted in significant differences (Table II). Finally comparing the mean results of the Pre 2 and Post questionnaires showed no significant difference ($p > 0.16$; Table II). The lack of significant difference between these two assessments indicates that the Pre 2 or Post questionnaires were similar indicators of class improvement as a result of this lab.

Individual question scores (proportion correct) from all three questionnaires are shown in Table III. Students appeared to have consistent difficulty with questions 3 and 7 on all questionnaires. Question 3 involved the trade-off between force magnitude and force duration for impulse production and question 7 involved the effect on the ballistic path of the center of mass (CoM) after contact (either foot to ground in jumping or hand to projectile in throwing). Both of these concepts are complex and involve results that are in general contradictory to popular understanding. However, even for these difficult concepts, the proportion of correct responses doubled between the first and second administration of the preassessment questionnaire (Table III). Students initially had substantial difficulty with question 8 as evidenced by the low proportion of correct responses on Pre 1 (Table III). As with question 7, question 8 involved the concept that the path of CoM of an object is responsive only to the forces applied to it. In the case of a slow moving projectile of a jumping individual whose feet have left the ground (where air resistance can be neglected), the only force applied is gravity. This is a fundamental principle of ballistic flight of a projectile. Students showed greatly improved understanding of this important concept on both Pre 2 and Post questionnaires by increasing correct responses approximately fourfold.

In contrast to questions 3, 7, and 8, students consistently performed well on questions 4, 5, and 6. In particular students achieved the highest proportion of correct responses on question 5. This question dealt with muscles behaving like springs. Perhaps scores on this question were influenced by material previously covered in lecture in this course, or in previous courses. This particular class was largely composed of exercise physiology majors who would likely have been familiar with the functional characteristics of muscle.

Finally, comparing the proportion of correct responses to individual questions on the Post questionnaire with the results of both administrations of the preassessment questionnaire, performance on the Post Questionnaire was intermediate (Table III). This likely indicates that a questionnaire that does not reiterate the material covered in the laboratory exercise is a more rigorous assessment of the progress made by the class in synthesizing the concepts dealt with.

Discussion

Nearly 2000 years in advance of Newton's formalization of the Laws of Motion in the seventeenth century, the Ancient Greeks discovered an application of these principles for long jumping. Aristotle (1912) writes in *De Incessu Animalium*, "That is why athletes jump further with weights in their hands than without" (Aristotle, *The Works of Aristotle*, Translation: A.S.L. Farquharson). Thus, from their keen interest in athletics, the Ancient Greeks were able to exploit fundamental principles of physics to improve performance, even if unaware of the formalized mechanics involved. In this laboratory exercise students are able to directly demonstrate that adding handheld mass can increase jump performance. This result will almost certainly be contrary to their expectations. The direct demonstration of this phenomenon stimulates their interest in understanding why this should occur. The results can only be explained through a formal understanding of impulse.

The experiment reveals that jump distance can be increased by the addition of handheld weights as seen in Fig. 1. This simple laboratory experiment confirms results recently available in the literature (Minetti and Ardigó, 2002). Detailed analysis indicates jump distance can be increased by approximately 5–7% for a vertical jump using handheld weights of optimal total mass. The optimum for a conditioned adult male occurs within the narrow range of 5- to 6-kg total mass (Minetti and Ardigó, 2002).

This lab exercise is a worthwhile tool for stimulating the engagement of students in the process of understanding important physical interactions underlying the function of the musculoskeletal system. We must caution that carrying dumbbell weights in the hands while jumping can be cumbersome and dangerous. Great care should always be exercised when conducting this experiment. We have specifically outlined in the overview for this exercise a number of associated potential hazards that we take special care to avoid. To date, our students have not suffered any harm greater than the normal muscle soreness often associated with participating in a new activity. It is our impression that the most useful safety protection is making the students aware of the hazards and reminding them to take care of themselves and their labmates.

Having demonstrated, against expectation, that carrying halteres of moderate mass increases jump distance, the question remains, what is the mechanism(s) that explain this result? To understand this, the mechanics of jumping need to be explained. We end the laboratory exercise with a discussion of jumping mechanics. We find that having determined that handheld weights are able to increase jump distance, the students are interested in discussing the subject. They usually also have a number of explanations they have formulated themselves that serve as discussion points. Below we describe our understanding of the influence of halteres on jump distance.

Biomechanics of Jumping

Prior to evaluating the influence of halteres on increasing jump distance it is necessary to understand the physics involved with jumping. In a jump the body is launched from the ground as a projectile and the flight of the individual's CoM will be determined by the velocity at takeoff (the instant the feet lose contact with the ground). Having a given mass, the individual's velocity will be dependent on momentum:

$$P = m \times v \tag{1}$$

where P is momentum, m is mass, and v is velocity of the individual's CoM. The change in momentum (going from a standstill to takeoff velocity) is determined by the impulse the individual has applied to the ground. Impulse is simply the product of force and time:

$$\text{Impulse}\,(Ns) = \text{Avg. Force}\,(N) \times \text{Time Applied}\,(s) \tag{2}$$

This concept is derived from Newton's 2nd Law of Motion: impulse/momentum where force × time = mass × velocity (Sears *et al.*, 1980). At this level, the impulse–momentum relation is a simple rearrangement of the more commonly expressed form of Newton's 2nd Law; $F = ma$ (force = mass × velocity/time ≡ force × time = mass × velocity) (Bueche, 1972).

For a constant mass system such as an individual, the larger the impulse, the greater the takeoff velocity. Large impulse can be generated by either a large magnitude average force over a brief time or by a moderate average force applied over a longer time. It is usual to assume that jump distance is determined by force production. This is derived from recognizing that human limbs have a finite length, and once they reach their fully extended position, the feet must leave the ground. Thus, the time available for force production is largely limited by leg geometry. For a given individual increases in takeoff velocity or jump distance must come from increases in average force applied. When parts of the body other than the legs are considered, however, mechanisms of impulse transfer become evident and subtle changes in the time over which force is applied can contribute to changes in takeoff velocity and consequently jump distance. To understand this, it is necessary to assess the movements involved in a jump.

At the initiation of a jump the individual will flex their knees, bend over at the waist, and swing their arms backward. Even though all of these motions move the individual in a direction opposite to their goal, these motions are a logical preparation for accelerating the body forward. Knee flexion is necessary to allow for the extension of the legs. Greater extension at the knees allows muscle force generated in the legs to be applied over a longer time period, increasing the applied impulse. However, it will be noted that if an individual flexes the knees and then stops in a crouched position, the individual will not be able to achieve the same jump distance as would be possible with a continuous movement. In the continuous movement the body dynamically "bobs" downward and immediately extends into the jump. This is known as a countermovement jump (Harman *et al.*, 1990).

Flexion at the knees causes stretching of the knee extensor muscles allowing them to convert gravitational potential energy from the movement of the body downward to elastic strain potential energy in the muscles and tendons of the leg (Alexander and Bennet-Clark, 1977). Strain energy can then be recovered and utilized by the legs to accelerate CoM upwards and forwards (Anderson and Pandy, 1993). Effectively, knee flexion loads the leg muscle/tendon springs (Blickhan, 1989; Farley *et al.*, 1993) (Fig. 2(A)) which enhances the force (Alexander, 1990) and

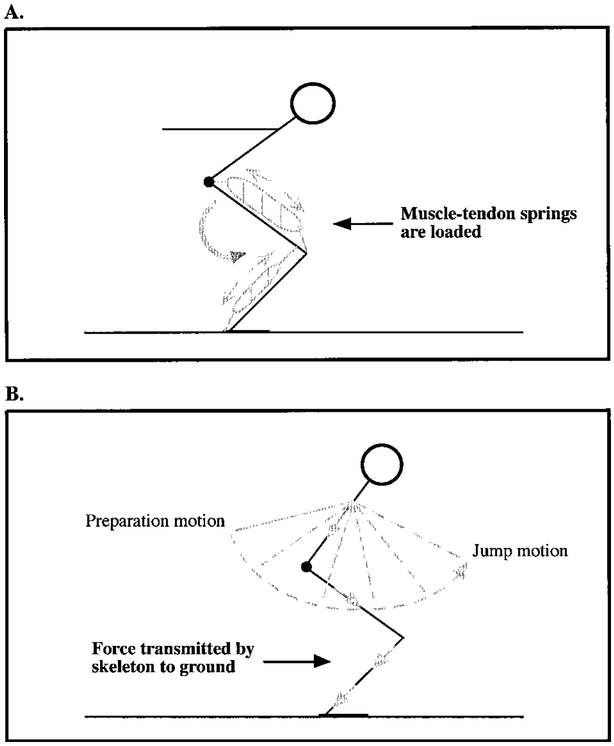

Fig. 2. Leg, trunk, and arm function in jumping. (A) Flexion of the knees prior to jumping or a countermovement involves a rapid leg muscle and tendon stretch immediately followed by extension of the head, torso, and legs. Ballistic stretching of the leg muscle/tendon springs allows them to store and return elastic strain energy. The magnitude of the force applied to the ground increases also because of stretch potentiation and contraction velocity changes of the muscles themselves. Knee flexion also increases the time of force application to the ground which is critical for large applied impulse. (B) Acceleration of the arms backwards then forwards in sequence with extension of the head, trunk, and legs increases the body's momentum at takeoff above that which could be achieved by the legs acting alone. Force generated by arm and shoulder muscles to accelerate arms forward and upward acts downward on the skeleton; effectively increasing GRF, applied impulse and CoM (filled circle) takeoff velocity. Arm swing also displaces CoM horizontally to a more anterior position with respect to the feet and causes forward rotation of the body about CoM just prior to takeoff.

power output of the leg muscles and in turn increases the average force applied to the ground (Minetti and Ardigó, 2002). Moreover, ballistic stretching of muscles increases the firing frequency of the muscle spindles (stretch receptors) and may result in reflex contraction facilitation (Melvill-Jones and Watt, 1971) which would further increase force (Bosco and Komi, 1979) and thus applied impulse. Obviously leg function in jumping can be complex. What of motions in the other segments of the body?

Flexion of the trunk at the hip allows for extension during the jump, just as flexion at the knee does. By flexing the trunk, muscles of the posterior aspect of the back, pelvis, and leg can be used to accelerate the mass of the trunk and head prior to and/or concurrent with the action of the legs. Flexion prior to the initiation of the jump means that the forces accelerating the trunk and head can be applied over a longer time period, ultimately translating to a greater applied impulse. Careful observation will indicate that trunk extension actually precedes much of the leg extension in the jump. This allows the upper part of the body to be accelerated, using muscles not directly associated with the extension of the knee and the ankle. Therefore, the initial acceleration of the trunk and the head does not depend on leg musculature. Acceleration resulting from leg extension adds to the initial velocity of the trunk, a portion of the body that has already been accelerated by intrinsic musculature. This means that the final takeoff velocity of CoM must be greater than the legs would have been capable of achieving on their own.

Preceding extension of the trunk in the initial phase of a jump, the arms are swung forward. Just as in extension of the trunk, the mass of the hands and the arms are accelerated by shoulder musculature prior to the extension of the legs. Like the trunk, leg extension simply adds acceleration to the arm and the hand masses after they have been accelerated by muscles not residing in the legs. By using a sequence accelerating the mass of different segments in the body, muscles of the trunk and the shoulders can be recruited to increase body momentum at takeoff above that possible with leg musculature alone.

Like the legs however, the function of arm motion in jumping tends to be more complex. The overall increase in body momentum at takeoff is in part the consequence of a subset of events brought about by accelerating the arms upwards and forwards; namely greater takeoff velocity of CoM (Ashby and Heegaard, 2002) and increased force applied to the ground by the leg muscles (Feltner *et al.*, 1999). In the latter case upward swinging of the arms adds to the downward force on the rest of the skeleton (Harman *et al.*, 1990) (Fig. 2(B)), thus slowing the contraction speed of the leg muscles allowing for greater force and power generation (Hill, 1938). Acceleration of the arms also increases horizontal displacement of CoM with respect to foot contact at takeoff and landing (Ashby and Heegaard, 2002). Furthermore, immediately prior to takeoff, the forward acceleration of the arms pitches the body rearward initially, then forward as the arms are decelerated at the end of their upswing by producing a ground reaction force (GRF) moment that causes destabilizing forward rotation of the body about CoM. At landing, greater horizontal distance between CoM (more posterior position) and the feet creates another situation for instability. Arm motion throughout the jump provides control for forward rotations of the body about CoM allowing a jumper to benefit from the additional horizontal displacement of CoM (Ashby and Heegaard, 2002).

Having established the basic mechanics of jumping, the influence of halteres on jump distance becomes clear. The addition of handheld weights causes the arm and the shoulder muscles to generate greater force to accelerate the hands in forward and upward arm swinging. Therefore, more force acts downward on the skeleton, greater force is applied to the ground, and overall impulse is increased (Fig. 3). Provided the halteres can be accelerated to at least the velocity CoM has at takeoff, without decreasing normal CoM takeoff velocity, jumping with halteres will not decrease jump distance. If the halteres can be accelerated to greater-than-normal takeoff velocity, the added impulse will contribute to the momentum of the entire system, that being the jumper and the halteres combined. Also, positioning of the arms and the halteres at takeoff will move CoM of the system more anterior adding to horizontal translation of CoM (Minetti and Ardigó, 2002). Proper timing of these events is essential, thus the rigorous practice conducted by the ancient athletes (Gardiner, 1930; Harris, 1966). Swinging of the arms and the halteres forward would also generate a larger forward directed GRF moment which may further increase horizontal displacement and translation of the system's CoM.

When the feet have left the ground, CoM moves in a ballistic path, i.e., a path that is influenced almost exclusively by the acceleration of gravity (a constant). CoM must follow a single parabolic flight trajectory (Fig. 3) and once the feet have left contact with the ground, the ballistic path of the whole system, the body and weights, is determined regardless of what is done with the arms, legs, or associated weights. Contrary to the expectations of many students, then, carrying weights in the air will *not* hinder this aspect of the jump. Full appreciation of this depends on recognizing that momentum changes require the application of an impulse, and in the air humans can only apply negligible external forces (e.g., air contact).

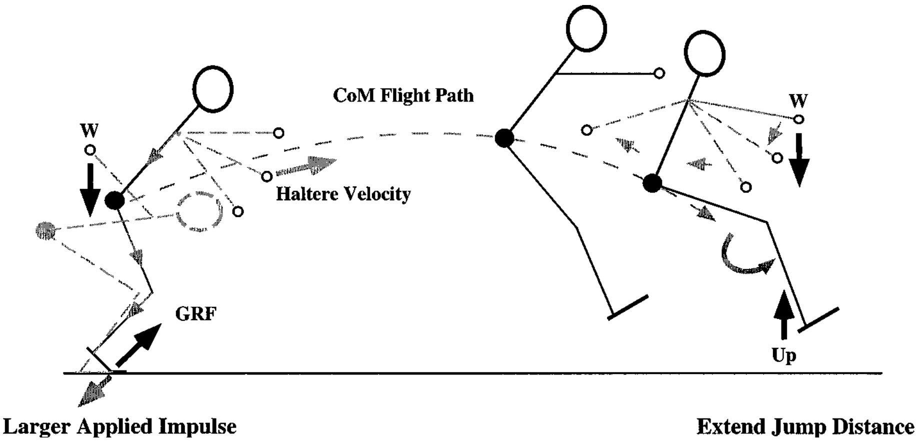

Fig. 3. Influence of halteres on jumping mechanics and jump distance. Acceleration forward and upward of the arm and haltere (small open circles) masses combined (left) increases force applied by the legs at takeoff resulting in greater applied impulse. Achieving acceleration of the arms and halteres forward beyond normal CoM takeoff velocity in sequence with acceleration of the trunk in extension (dashed gray stick figure) can add to the greater applied impulse and substantially increase overall momentum at takeoff, thus increasing jump distance. Additionally, position of the halteres relative to CoM during forward swing and a larger forward directed GRF moment just prior to takeoff further increase horizontal translation of the system's CoM (body + halteres). During flight, CoM follows a parabolic flight path that is unaltered by changes in limb position once the feet lose contact with the ground. In preparation for landing the arms are accelerated downwards and backwards (right) which causes the legs and feet to move relatively upward and forward as the system's CoM must follow the predetermined flight path. By the legs moving to a more forward position about CoM flight time is briefly extended and jump distance is further increased.

In preparation for landing measured jump distance can be influenced. Although the ballistic path of CoM cannot be altered while the weights are held, the relationship of the feet to CoM can be adjusted. When approaching the landing, long jumpers will accelerate their arms downwards and backwards. Since the combined CoM of the body and halteres progresses on a predetermined path affected only by gravity, by accelerating the arms and the halteres back and down, the remainder of the body moves up and forward (Fig. 3) (Minetti and Ardigó, 2002). This includes the legs and feet (where touchdown is measured) and may include a rotation about CoM to extend the jump even further (Tasch, 1952; Watson, 1954). Rotations about CoM through backward swinging of the arms should furthermore be necessary to correct for extra forward rotation about CoM imparted at takeoff (Ashby and Heegaard, 2002). Likewise, a more posterior position of CoM relative to feet at landing should require swinging of the arms forward just after contact to maintain balance. Observations of students jumping with weights confirm the use of this technique.

Thus, there are six mechanisms whereby halteres can increase jump distance: (1) increased arm/shoulder muscle contribution to total applied impulse, (2) storage of greater elastic strain energy in leg muscles and associated tendons, (3) increased muscle force generation through facilitation of limb muscle contraction via stretch receptor reflex potentiation and slowing of the contraction velocity (4) reorientation of the body about CoM of the combined body and halteres at takeoff and landing, (5) greater CoM horizontal displacement and translation by a larger forward directed GRF moment at takeoff, and (6) raising of the body relative to CoM through accelerating the halteres downward just prior to landing. Although it is likely that all six of these provide some influence on the jumping results determined in the laboratory exercise, it may be much more complex to determine the proportional contribution of each to overall jump performance.

Finally, the current interpretation of the mechanics by which halteres improve jump distance is substantiated by depictions of athletes practicing jumping with halteres on various Ancient Greek vase paintings. Although it has been plausibly concluded that the long jump event of the Ancient Olympiad pentathlon was probably either a double (Harris, 1966) or a triple jump (Ward-Smith, 1995) that made use of a shorter, moderate speed running approach (Gardiner, 1930; Harris, 1966), at least two vase paintings (400 B.C. Louvre, G.502; Leipsic, T.642) illustrate that athletes must have practiced their technique for accelerating the arms with halteres at takeoff by performing standing long jumps (Gardiner, 1930). In both of these paintings, the jumpers are seen to have their feet together, knees flexed and the arms in a mid-forward swing position; a form very reminiscent of sequential body segment accelerations following a countermovement.

It has also been suggested that halteres may help the athlete jump farther if the halteres were forcefully thrown away backwards in midflight (Harris, 1966), thus generating thrust, a clever application of Newton's principle of conservation of momentum (Tasch, 1952). However, the archaeological evidence clearly shows that during midflight and upon landing, athletes maintained possession of the halteres (Fig. 4). On the basis of current understanding of the mechanics of jumping, it is logical for a jumper to accelerate the weights downwards and backwards during the landing approach, while maintaining a grip on the weights. Again from artistic depictions on Ancient Greek vase paintings (~650 B.C. British Museum, B.48; ~600 B.C. New York Metropolitan Museum, o8.258.30) it is apparent that on the approach to landing, Ancient Greek long jumpers did swing the arms and halteres downwards and backwards (Fig. 4; Gardiner, 1930; Harris, 1966).

CONCLUSION

This laboratory exercise was designed to be an engaging experience that teaches students about the mechanical concept of impulse through the interesting application of handheld weights to increase jump distance. The use of halteres to increase jump distance is an ancient practice that is representative of the first documented employment of passive tools designed to increase human athletic performance (Minetti and Ardigó, 2002) and is highlighted by a history of use in the jumping sports of the ancient Olympiad. As such, the practice of jumping with weights is one that most students of human function and performance seem particularly curious about. An additional benefit of the lab exercise is the opportunity to teach students about applications of mechanics from both an historical and a performance-based perspective. Indeed, it is intriguing to establish a line of inquiry in the mechanics of human movement that dates back over 3000 years ago and to combine those early ideas with what modern science and technology have allowed us to discover about the mechanics of basic locomotory activities. Using this perspective, students are given

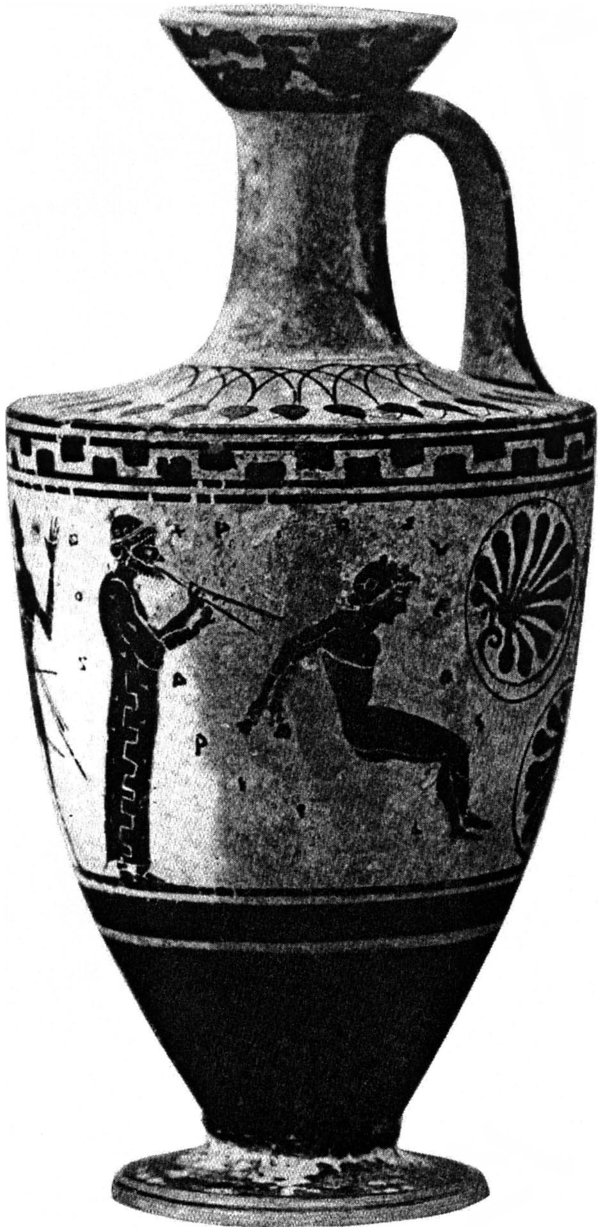

Fig. 4. An example of an Ancient Greek vase painting of haltere jumping. The jumper is portrayed approaching the landing holding the halteres in the hands after having accelerated them and the arms downward and backwards (Rogers Fund collection at the Metropolitan Museum of Arts, New York). After Harris (1966).

an opportunity to actively learn by revisiting ancient practices of exploiting principles of physics to improve jump performance. With some initial level of understanding of jumping, this laboratory exercise can be shown to be an effective teaching tool for improving students' basic understanding of the physics behind the motion.

APPENDIX A

Halteres Data Sheet

Subject	Jump	Distance (m)	Normalized distance (prop. leg length)	Normalized mass (% body mass)
Control: Jumping without weights				
A	1			
A	5			
A	9			
		avg.		
B	1			
B	5			
B	9			
		avg.		
Treatment: Jumping with weights				
1.4 kg				
A	2			
A	6			
A	10			
		avg.		
B	2			
B	6			
B	10			
		avg.		
2.3 kg				
A	3			
A	7			
A	11			
		avg.		
B	3			
B	7			
B	11			
		avg.		
3.6 kg				
A	4			
A	8			
A	12			
		avg.		
B	4			
B	8			
B	12			
		avg.		

APPENDIX B

Prelab Questionnaire

Each statement below contains true and false components about jumping mechanics. Choose the component that makes each statement true.

1. The distance or height of a jump depends most on
   a. the maximum force applied to the ground at jump takeoff

   b. the velocity of the individual at jump takeoff
2. To increase jump height or distance, it makes sense to
   a. accelerate lower body masses in advance of upper body masses
   b. accelerate upper body masses in advance of lower body masses
3. A greater magnitude of impulse for jumping can be generated by
   a. applying a large force to the ground for a very brief period of time
   b. applying a moderate force to the ground for a long period of time
4. Flexion of the knees prior to jumping is most useful for
   a. controlling the direction of the jump
   b. increasing the time over which force is applied to the ground
5. One role of muscles in jumping takeoff is to function as
   a. springs that store and return elastic strain energy
   b. shock absorbers that prevent energy levels from getting too large
6. Acceleration of the arms upwards by the shoulder muscles while the feet are in contact with the ground
   a. cannot increase maximum force applied to the ground
   b. can increase maximum force applied to the ground
7. Extension of the trunk at the hips just after the feet have left the ground
   a. cannot increase jump height or distance
   b. can increase jump height or distance
8. The path of the body's center of mass (CoM)
   a. cannot be changed once the feet leave the ground
   b. can be changed by acceleration of the arms and legs relative to the body after the feet leave the ground
9. For a given takeoff velocity, the path of the body's center of mass after the feet leave the ground
   a. is different depending on the amount of mass an individual carries when jumping
   b. is not different depending on the amount of mass an individual carries when jumping
10. Neglecting air resistance, the horizontal velocity of an individual prior to landing
   a. is different than the individual's horizontal velocity at jump takeoff
   b. is not different than the individual's horizontal velocity at jump takeoff

Postlab Questionnaire

Each statement below contains true and false components about throwing mechanics. Recognize that the basic mechanics of throwing can in many ways be considered the inverse of jumping, where the objective is to accelerate an object away from the individual rather than accelerate an individual away from the ground. In answering the following questions use the concepts learned in the halteres lab to choose the component that makes each statement true.

1. The distance or height of a throw depends most on
   a. the maximum force applied to the object at throw release
   b. the velocity of the object at throw release
2. To increase throw height or distance, it makes sense to
   a. accelerate lower body masses in advance of upper body masses
   b. accelerate upper body masses in advance of lower body masses
3. A greater magnitude of impulse for throwing can be generated by
   a. applying a large force to an object for a very brief period of time
   b. applying a moderate force to an object for a long period of time
4. Flexion of the elbow prior to throwing an object is most useful for
   a. controlling the direction of the throw
   b. increasing the time over which force is applied to the object
5. One role of muscles in throwing is to function as
   a. springs that store and return elastic strain energy
   b. shock absorbers that prevent energy levels from getting too large
6. Acceleration of the legs by lower body muscles while the object is in the hand
   a. cannot increase maximum force applied to the object
   b. can increase maximum force applied to the object

7. Rotation of the trunk at the hips just after the object has left the hand
   a. cannot increase throw height or distance
   b. can increase throw height or distance
8. The path of the object's center of mass
   a. cannot be changed once the object leaves the hand
   b. can be changed by any rotation of the object after the object leaves the hand
9. For a given release velocity, the path of the object's center of mass after the object leaves the hand
   a. is different depending on the mass of the object being thrown
   b. is not different depending on the mass of the object being thrown
10. Neglecting air resistance, the horizontal velocity of the object prior to landing
    a. is different than the object's horizontal velocity at throw release
    b. is not different than the object's horizontal velocity at throw release

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