HARVESTING ELECTRICAL ENERGY WITH ELECTROACTIVE POLYMERS
PART I. BIOMECHANICAL AND PHYSIOLOGICAL CONSIDERATIONS

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Abstract

Man has become more dependent on technology in all arenas of life. The ubiquitous use of mobile technologies requires that constant electrical power, presently provided by batteries, is available. Total dependence on batteries is problematic because short battery lifespan requires larger batteries, and battery weight can become a significant issue. In the case of the military, carrying batteries becomes a backbreaking load (packs weigh in excess of 80 lbs) which limits the time soldiers can remain in the field. A device that could generate significant electrical energy to recharge batteries while one is on the move, would provide greater freedom and operational ability.

Energy "harvesting" from body movements requires the capture of mechanical energy and conversion into electrical energy. Up to now, attempts have been extremely limited in terms of wattage (i.e., 10-20 milliwatts) [1,2]. This is because work done by muscles during locomotion is generally inaccessible. The only place that is relatively accessible, the foot (placing piezoelectric devices in the shoes), is a relatively poor location for extracting mechanical energy because very little mechanical work is done at the foot during locomotion.

The key requirement for many electrical energy-generating technologies, such as electroactive polymers, is the ability to produce movement against a load (i.e., provide the mechanical work which will be converted to electrical energy.) Based on a biomechanical analysis, we have developed a strategy and device (suspended-load backpack) which can produce large forceful movements. These movements, when coupled with artificial muscle energy-generating technologies (see Zhang et al. 2003, in this volume [3]), should permit the generation of several Watts of electrical energy during normal walking movements.

Introduction

Man has become more dependent on technology in all arenas of life: Wireless and mobile technologies used in business, medicine, recreation, and military all depend upon electricity, presently provided by batteries. Total dependence on batteries is problematic. In the case of the military, carrying batteries becomes a backbreaking load (packs weigh in excess of 80lbs) which limits the time soldiers can remain in the field. In other cases (laptops, cellular phones, and job-specific electronics in medicine, business, and recreation), the dependence on battery power limits our daily activities as one is often in search for AC outlets. A device that could generate significant electrical energy to recharge batteries while one is on the move, would provide greater freedom and operational ability.

Up to now, electrical energy harvesting from body movements has been extremely limited in terms of wattage. A watch which stays powered by arm movements generates on the order of a few thousandths of a Watt (milliwatts) or less. Devices put in shoes to harvest electrical energy during walking have been able to develop only 10-20 milliwatts [1,2]. There is a strong need to develop a device capable of harvesting energy on the order of Watts, particularly for military applications.

To achieve this goal, it is necessary to use a multidisciplinary approach that combines the capabilities of physiologists/biomechanists and engineers. An engineering approach in the absence of physiological/biomechanical measurements is very limiting. This is because even if a device is developed which can convert some mechanical energy to electrical energy, it might not be placed in the optimal anatomical position for extracting mechanical energy. Further, the device might cause stability, maneuverability or orthopaedic problems, or it may be very energetically costly to the soldiers, requiring a higher metabolic rate and causing more rapid fatigue. Thus we must combine physiological and biomechanical approaches with engineering approaches to identify the best positions for energy harvesting and to form a set of physiological/ergonomic criteria which must be met by the device.

From the engineering point of view, there are also many issues to be addressed in order to maximize the energy harvesting from the extracted mechanical power at various locations on the human body. As described in the accompanying paper by our colleagues at Penn State (Zhang, Hoffman, Liu and Ren; [3]), three new approaches will be taken in this project: (1) the mechanical impedance of the energy-converting will be matched to the mechanical energy extraction device, so that power can be effectively transferred from the mechanical sources to the electroactive materials; (2) we will make use of the newly developed electroactive materials which possess high elastic density and higher electromechanical conversion efficiency than the piezoelectric materials used in earlier attempts of energy harvesting; (3) special electronic circuits will be developed to achieve high (>50%) electric power extraction from the electroactive materials.

In this paper, we examine the energetics and mechanics of human movement with a view of choosing a means of extracting mechanical energy which can be subsequently used for electrical conversion. We describe a device that one of us developed (suspended-load backpack) which effectively makes mechanical energy accessible for conversion to electrical energy. We also discuss how use of this device may reduce shoulder forces which in turn will reduce orthopaedic problems and may permit the carriage of greater weights.

Limits of Human Performance

Human performance has been studied extensively for decades, so as a first step we can ascertain how much energy is available for harvesting. The values vary greatly depending on the duration of performance as well as what proportion of the subject's muscle mass is included in the activity (i.e., activities which use a greater proportion of the muscle mass naturally can generate more power).

Total energy usage vs. mechanical power output. Muscle is a biochemical machine which takes high energy compounds (fat, carbohydrates and proteins) and breaks them into lower energy compounds: CO_2 and H_20. Some of the energy released in this process is captured in the form of ATP, which in turn is the immediate fuel used by the muscle Ca^{2+} pumps and muscle cross-bridges. The cross-bridges, in turn, can use the energy in the ATP to perform mechanical work. The fact that there are three points at which energy can be measured (total energy, energy in the ATP, and the amount of mechanical work performed) and that two efficiencies can be determined (mechanical power output/total energetic cost or mechanical power output/energy stored in the ATP utilized) can lead to some confusion. As a rough guideline, approximately half of the chemical energy that is liberated in the breakdown of metabolites is captured in the form of ATP, the rest is liberated as heat. Further, a maximum of about 50% of the energy stored in the high energy phosphate bond in ATP can be converted to mechanical power (note, that this value is highly variable and depends on the activity in which the muscle is engaged–i.e., if muscle generates force isometrically and thus does not shorten, then no external work is done and the efficiency is zero!) (See Rome, 2003, in this volume [4]). Hence when describing the efficiency of mechanical power generation in terms of the energy contained in the bonds of the metabolites, the maximum value is approximately 25%. Note that although this seems low compared to some artificial muscles, this is misleading. The 25% value is equivalent to calculating the efficiency of an electric motor by going back to the energy in the coal that is burned to generate the electricity in the first place.

Short duration–maximal performance. Man is capable of generating large amounts of power for a short period of time. For example, a well-trained cyclist can generate in excess of 1200W of power over one half-crank revolution [5, 6, 7]. The amount of power a person is capable of generating for short periods depends on the amount of muscle mass being recruited. In the case of cycling, lean thigh mass is a good predictor of maximal short-term power [6]. Since college-aged males tend to have smaller lean thigh mass than well-trained cyclists, they will typically generate less power over a short period (i.e. 800-1200W) while elite sprinters, with larger lean thigh volumes, will exceed 2000W. Other modes of exercise incorporating a greater amount of lean body mass will yield higher short-term power outputs. For example, elite rowers can average greater than 2000W of power generation over the drive phase of one stroke. In this whole body motion, maximal power is correlated to total lean body mass [8]. It is likely that muscle efficiency at these maximum power outputs, would be reduced to 10 or 15%; however, for technical reasons, it is very difficult to measure. Indeed, if it is reduced to 10%, then when the athlete is generating 1500W of mechanical work, the total energy utilized would be an extraordinary value of ~ 15,000W!

If even a tiny fraction of the total energy could be converted into electricity, this would be a very large source of electrical power. Alas, there are two unfortunate facts. First, there isn't an easy technology to convert heat into electricity from the small heat gradients in the body. Second, this level of athletic activity can only be maintained for 5 to 10 seconds.

Sustainable power output. The reason that this maximum level of performance cannot be sustained for long periods is that ATP cannot be generated fast enough. Even if there is a significant reduction in the performance level, where ATP can in fact be generated, this can only be done anaerobically and thus on the order of only minutes (Fig 1). To break carbohydrates down to CO_2 and H_20, oxygen is necessary. If sufficient O_2 cannot be delivered then the carbohydrates must be broken down anaerobically to lactic acid. When lactic acid builds up, it causes the muscle to become more acidic, thereby reducing the force production and causing fatigue. Hence, the generation and build up of lactic acid sets the limits for sustainability in high intensity exercise. Over the course of several hours, for an elite cyclist, the lactate concentration is mostly dependent upon lactate threshold. Professional cyclists typically have a maximum oxygen consumption rate (VO_2max) of around 5.2-6.0 L/min and a lactic threshold of around 80-85% VO_2max [10]. Using the ACSM equation (which is an empirical equation relating oxygen consumption to mechanical work production [11]), we would expect a sustained mechanical power output of 320-410W, which is in fact about what an elite cyclist would hold for a long time trial. For average college aged males, the lactate threshold would occur at about 150-200W, which also constitutes a very high level of activity.

Walking Metabolism. It is clear that when carrying 80 lb or larger loads in the battlefield, cycling, rowing, or even running (which has a clear aerial phase) are not possible-- hence the mode of movement will be walking. For walking at various speeds, the energetic cost varies with walking speed (and body weight and/or load carrying). The value of total metabolism ranges from 200-350 W. It is difficult to ascertain how much mechanical work is done during walking, because unlike sprinting (where there is acceleration), or cycling and rowing (where mechanical work is being performed against the crank or a lever system), measurement of mechanical work performed during walking is complicated to assess (see below).

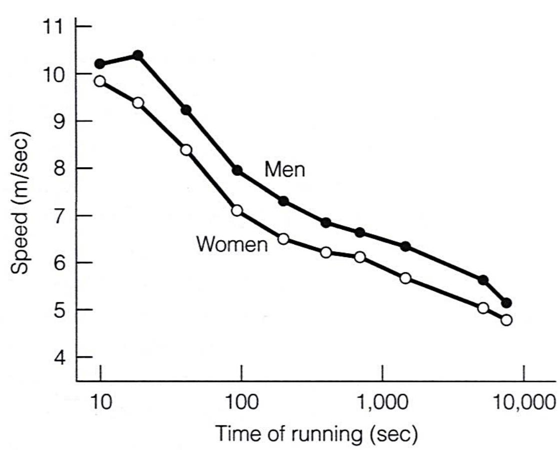


Figure 1. Average running speed maintained vs time of event for World records. From [9].

Mechanics and Work Production During Walking

Terrestrial locomotion is fundamentally different than locomotion through a fluid. In fluids, the environment does work on the body moving through it (by the force of drag) and the animal must perform mechanical work on the environment (by the force of thrust). In terrestrial locomotion, the environment does no work on the body except for the small force of aerodynamic drag which is tiny during human movement. Conversely, humans do no work on the environment (i.e., there is no significant wake or vortices or an increase in temperature left behind).

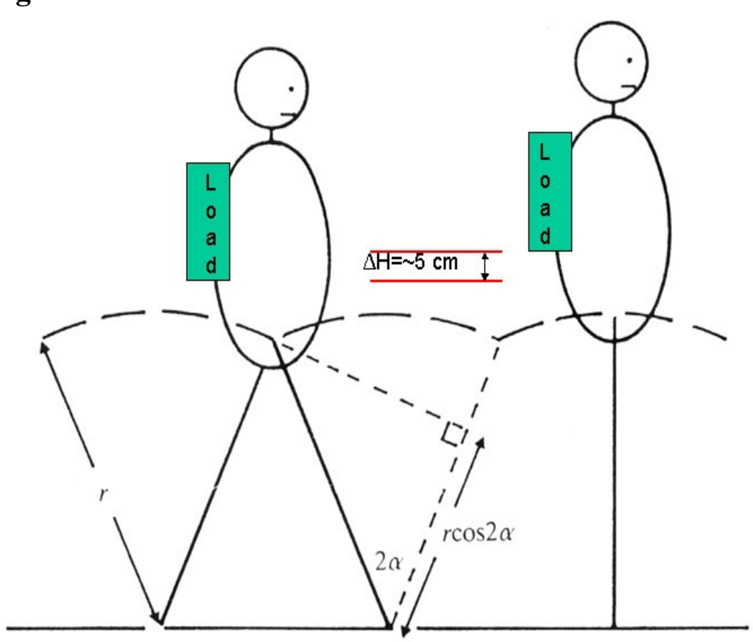
When running, the mechanical energy (based on measurement of the kinetic and gravitational potential energy of the body) stays essentially constant during the aerial phase (i.e., there is transfer between kinetic energy in the vertical plane and gravitational potential energy as the height of center of mass (COM) changes). However, the mechanical energy (sum of kinetic and gravitation potential) declines when the foot makes contact with the ground. This loss of mechanical energy is accomplished by negative work performed by the muscle-tendon complexes distributed around the joints. At takeoff, this energy must be placed back into the mechanical system so that the animal has the same level of mechanical energy as it did before it hit the ground. The source of this mechanical work depends on the fate of the mechanical energy absorbed during the deceleration. If it was lost as heat, then the muscle must perform mechanical work *de novo*, to reaccelerate and add an increment of mechanical energy to the body. However, if the mechanical energy is stored in the stretch of elastic structures (tendons, muscle, ligaments), then this stored elastic energy can be put back into the system by the muscle-tendon complex performing positive work. Determining how much of the energy increment is lost as heat or is stored as elastic energy and recovered during lift off, is difficult to measure. There have been superb experiments (involves determining the force on and the strain of the tendons during the contact phase, [12, 13,14]) which suggest that in man a great deal of the energy can be stored and recovered. Hence, the contractile element of the muscle doesn't have to perform as much *de novo* mechanical work as it would otherwise, thus reducing the energetic cost [15, 16, 17, 18].

Walking, of course, is energetically less costly than running, and this is in large part due to the fundamentally different mechanism for mechanical energy transfer employed during walking. While walking, a person's movement is like an inverted pendulum [19]: one foot is put down, then the body vaults over it, then the back foot is brought forward and put down, and then the body vaults over that one (Fig 2). Although the hip and center of mass go up and down 4-5 cm, mechanical energy is transferred between gravitational potential energy and kinetic energy, hence in theory very little *de novo* mechanical work needs to be done by the muscles. Muscles, of course, are required to perform mechanical work to swing the legs forward and to add increments of mechanical energy inevitably lost to energy transfer inefficiencies and friction. In addition, one still needs the muscles to generate force and hold the leg relatively rigid as the subject vaults over it. Generating force, however, is energetically less expensive than performing mechanical work (See Rome, 2003, in this volume [4]), and thus walking is energetically cheaper than running.

Extracting Mechanical Energy out of Human Locomotion

One result from the preceding analysis is that almost all of the mechanical work is done

Figure 2



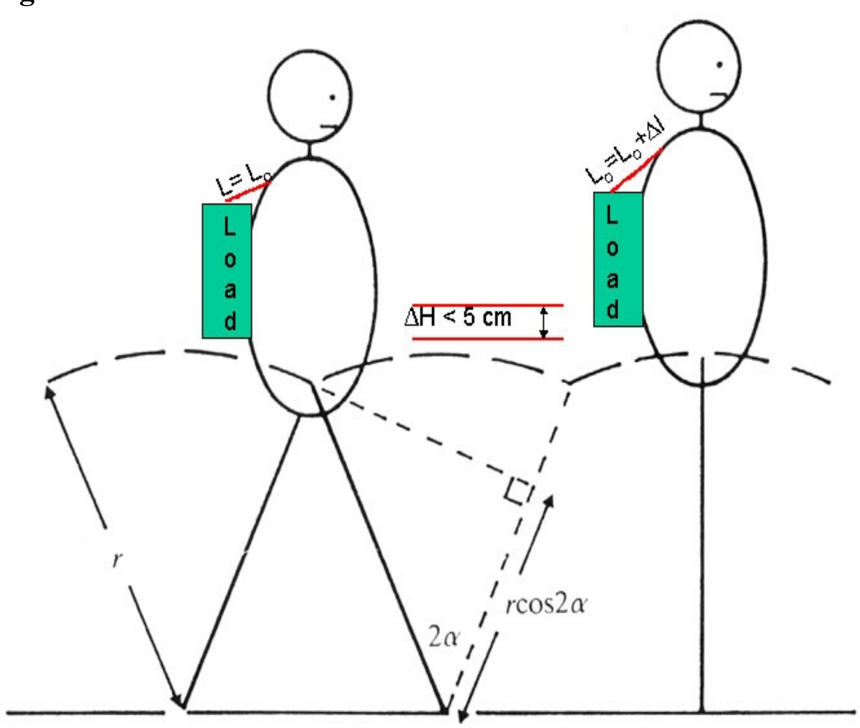
inside the body (rather than on the environment). This makes it exceedingly difficult to extract some of the mechanical energy to drive the electrical energy conversion apparatus because the device would need to either be placed in the body (which is difficult) or attached to the outside of the body (i.e. like an exoskeleton or kneepad) which affects maneuverability and comfort. Therefore, the most obviously place to put a device is in the shoe, but this has permitted only small levels of electrical energy generation. The chief reason for this limitation is that essentially no work is done at the foot-ground contact point, and thus there is very little mechanical energy which can be extracted.

This can be clearly appreciated when observing the contact between the boot and the ground. Although very large forces can be generated, very little work ($\int F \cdot dl$) is done because under normal circumstances the point of force application does not move (i.e., $dl=0$). One can artificially try to make the system perform work by making the boot compliant (and hence have the foot move a small distance in the shoe) or by placing a sole plate which is deformed as one moves from heel strike to toe off. In both of these cases, this distance (and hence the mechanical energy available for extraction) is limited because as the boots become more and more compliant, it affects the subjects' ability to move and maneuver.

An analysis of humans walking with backpacks, however, has yielded a possible mechanism for extracting mechanical energy. Although the large load in the backpack represents a significant problem for the subjects carrying it, one of us viewed it as an opportunity, and developed a way to extract some mechanical energy for eventual conversion to electricity.

As mentioned above, while walking, a person's movement is like an inverted pendulum [19]: one foot is put down and then the body vaults over it causing the hip to cycle up and down 4-5 cm. Any object rigidly attached to the body also has to move up and

Figure 3



down. Thus if one is carrying a load in a backpack, because it is fixed to the body, it has to go up and down that same vertical distance (Fig. 2). A considerable amount of mechanical work is done if the load is heavy. In the case of an 80lb load (36 kg), 18 J of energy accompanies each step (assume 5 cm displacement). This mechanical energy is also inaccessible if the load is rigidly attached to the body. The goal, therefore, was to decouple the movement of the load with respect to the body so that the differential movement created (between the load and the body) can be used to drive the electricity-generation technology employed.

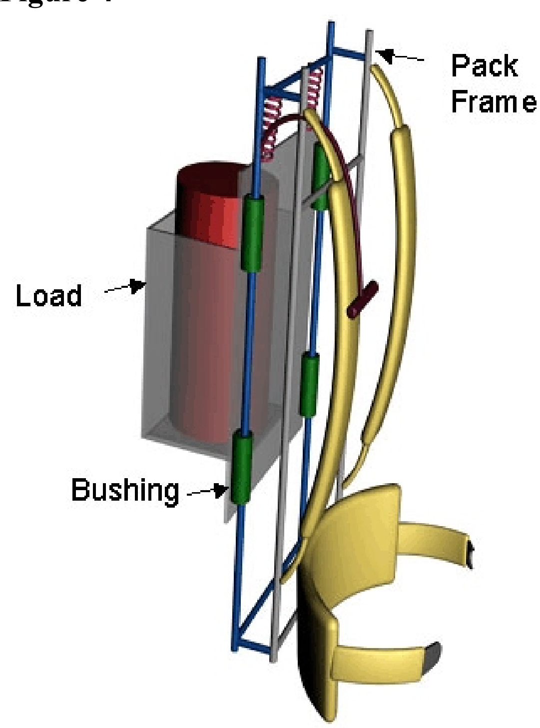
The simplest approach is the use of compliant shoulder straps (Fig 3). However the differential movement might cause the backpack to rub on the hips, back and shoulders and thus cause discomfort. An alternate solution is to have the pack frame fixed to the body, but to suspend the load from the frame, so that the load would still be decoupled from the body. One design prototype of the suspended-load pack is shown in Figure 4. During walking, the load would ride up and down on bushings (green) constrained to vertical rods (blue). Hence, the load would be free to move in the vertical direction without danger of swaying. Note that it is also possible to lock the load to the pack to prevent it from moving.

The backpack offers a unique opportunity to harvest energy from a walking subject. Depending on step frequency and hip excursion, 17-36 W are required to raise and lower the load. Although it is difficult to extract the mechanical energy from the body's change in height of the center of mass, by interposing this device between the body and the load, some of the mechanical energy changes of the load can be captured.

Additional Physiological, Biomechanical and Ergonomic Considerations and Approaches for Harvesting Energy

If there was not a human involved, that is if the human could be simply replaced with an actuator which undergoes a 5 cm height change at a constant 1.5 Hz, then the biomechanist/physiologist job would be done. After the initial biomechanical analysis of what type of device to use and where to place it, the engineers could take over and optimize the system to maximize the extraction of mechanical energy and conversion to electrical power. However, humans cannot be replaced by an actuator, as the way they move, their comfort, health and their mobility will all be influenced by the device and methodology used to extract the mechanical energy and convert it to electrical energy. One of the most important points is whether the magnitude of the hip excursion changes during walking with a weight vs walking with no weight. There is some controversy in the literature on this point. Some of the information suggests that it does change and thus that there is an interaction between

Figure 4



external forces (from weight of the pack) with the movement that humans make [20]. Yet more to the point, there is no information in the literature on how one's gait would change if the load was uncoupled from the pack nor how it would change if there was variable coupling (resulting from the energy conversion process). Therefore the optimization and analysis of the system cannot be undertaken without making a series of measurements on humans.

What are the optimal configurations for the suspended-load backpack and energy conversion device? The suspended-load backpack can certainly extract mechanical energy; however, considerable additional measurements and analyses are necessary to determine how important variables (e.g., compliance of electro-active polymers) should be adjusted to maximize power generation while minimizing biomechanical problems. It is recognized that the best device will need to be a compromise between ergonomics, mechanical power extraction and power conversion efficiency. Thus it is necessary to measure the biomechanics to obtain a range of ergonomic solutions that can be used to guide the engineering of the suspended-load backpack so as to maximize energy harvesting and conversion. With both sets of information, an "optimal" (or compromise) solution can be found. Once the "optimal" solution is found, an extensive set of experiments to quantify the amount of power converted under a variety of locomotion modes and speeds will be performed. These data will be used to further refine the backpack.

What are the physiological/ergonomic consequences of a particular device? Even with finding what appear to be optimal settings of the device for extracting mechanical energy and converting it to electrical energy, there remain a number of physiological, biomechanical, orthopaedic and ergonomic consequences of any device. In boots, for instance, having a thick compliant sole which is compressed by 5 cm on every foot-fall, would permit considerable mechanical work to be done, and thus significant energy conversion, on every step. However, this would have many negative consequences in terms of stability (carrying a heavy pack may result in falls), in terms of maneuverability (rapid accelerations may no longer be possible), it would likely increase the energetic cost of locomotion (as has been found for walking in sand or snow), and finally it could well result in orthopaedic problems. Clearly, these impacts must be ascertained in a quantitative manner before any device or approach to harvesting energy can be accepted:

1. Does the pack and mass form a stable system for carrying? We will measure the kinematics of the body as well as that of the pack during walking on a treadmill. Although it is not anticipated, if we observe swaying of the load or pack, this will alert us to a problem. Of course the subjects' own perceptions of stability will provide crucial information as well.

2. Is the pack and mass stable during rapid maneuvers? In theory, the pack system could be stable during normal walking, but could adversely affect a soldier's ability to move rapidly, which is also a crucial part of their repertoire of movements. This potential problem will be quantitatively evaluated by measuring the kinematics of the pack with respect to the body during rapid movements. The backpack is already fitted with a lock which can be engaged manually to prevent the load from shifting along the rails when it is inappropriate to do so. If load shifting during rapid movements becomes a significant problem, a lock which engages automatically will be developed.

3. Does wearing the pack increase the metabolic cost of locomotion above that with a normal pack? It is well know that carrying a load increases the metabolic rate. If carrying a given weight increases the amount of energy expended over and above that when using a traditional fixed pack, this may be a problem as it may result in early fatigue. Data from the study by Kram [21] (see below) show that although the metabolic rate increases with carrying a load, the metabolic cost was the same whether or not the load was suspended by the flexible pole. The metabolic rate needs to be compared during walking with a freely moving load and with the load locked to the backpack frame. We anticipate that there will not be an increase in energetic cost for carrying a given weight. Further, because one would need to carry less weight in batteries, using the regenerating system should result in a substantial drop in the overall metabolic rate.

4. Does the pack cause any ergonomic or orthopaedic problems? Making kinematic measurements of the pack during various movements will provide some of the information. We will also have a number of subjects wear the packs on a fairly continuous basis to determine whether there are any unexpected problems.

Suspended-load Backpack Reduces Forces on Shoulders

Although the driving force for the original design was to produce electrical energy, based on our analysis, wearing the suspended-load pack will very likely reduce peak ground forces and more importantly, reduce forces on the shoulder. This in turn should lead to a reduction in fatigue and orthopedic problems and may permit the carriage of greater loads.

We usually consider a load only in terms of the force required while we are standing still. This considerably underestimates the problem. As mentioned above, when we walk or run, the hips rise and fall, and if the load is rigidly attached to the body, the load has to undergo the same change in height (Fig 2). This requires that the load be accelerated upwards on the upstep and hence more force be exerted up on the load. As most loads are carried on the shoulder, this increases the force and pressure on the shoulder. This added pressure can be very large. For instance, Kram [21] found that when people run with a weight attached to their shoulders that the peak force on the shoulders is approximately 2-fold higher than the static weight when the person is standing still (Fig. 7; the solid horizontal line at ~150 Newtons represents the shoulder force due to the static weight).

Man has long recognized, however, that this large increase in force on the shoulders can be removed if the load is suspended. As noted by Kram [21], merchants in Asia often carry loads at the end of long bamboo pools carried over their shoulders (Fig 5). By suspending the loads from springy poles, it was found that as experimental subjects run, the load stays close to the ground and does not undergo the large vertical excursions observed for the center of mass of the person (Fig 6, also see Fig. 2 & 3). Because it is not necessary to accelerate the load upwards on the up-step, the forces that are generated at the feet and shoulders do not have to increase above that necessary to support the static weight while standing still (See compliant pole trace on Fig 7).

Hence, two important facts are clear: 1) Movement causes the dynamic forces on the shoulders to be much larger than the static forces when standing still. Hence, dynamic forces during walking or running are likely to be an important determinant of orthopedic problems. 2) Suspending the load can reduce the dynamic forces on the shoulders down to

Figure 5. From Kram [21].

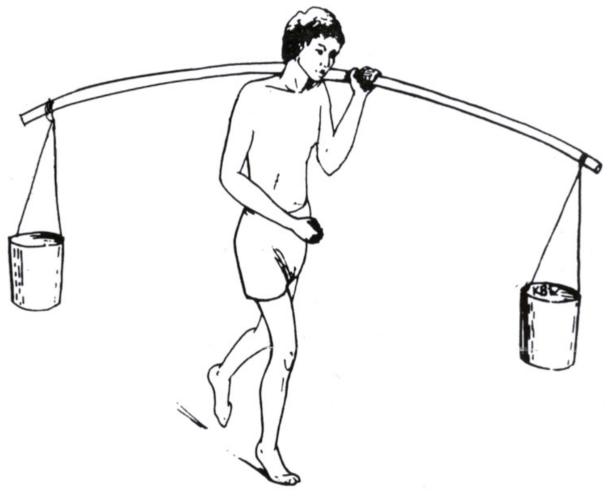


Figure 6. From Kram [21].

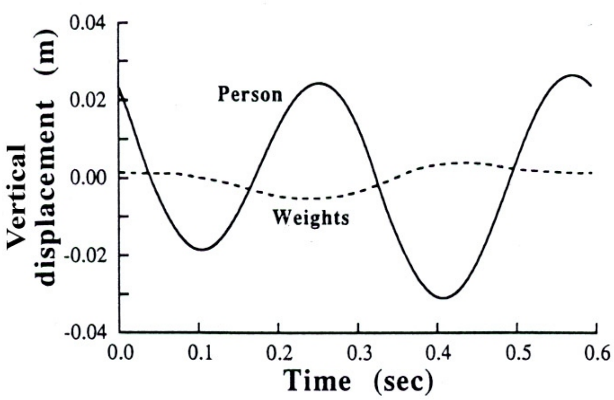
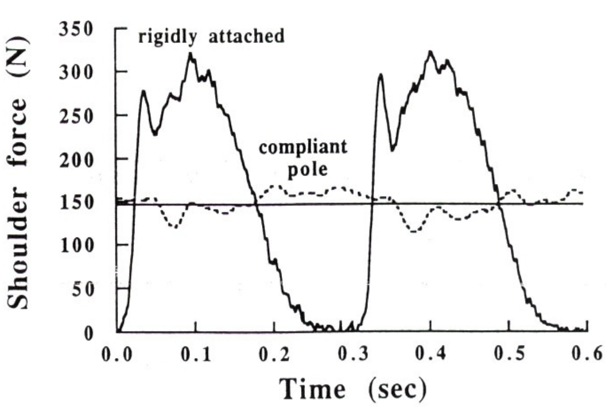


Figure 7. From Kram [21].



the level of the static forces when standing still (i.e., the weight), and hence may be an important avenue for reducing orthopaedic injury.

Load Carriage in Adults and Children

Clearly, any intervention which reduces dynamic force on the shoulders of adults has considerable importance for recreational backpackers and especially the military where load carriage is recognized as a major problem. Likewise as we become increasingly technology-dependent, there is a greater need for carrying laptop computers and even medical devices. Reducing the dynamic forces on the shoulders of the general public, and especially in the elderly, is of considerable interest, as well.

Importantly, this represents a potential opportunity to reduce the dynamic loads experienced by school children who carry heavy day-packs. There is significant evidence from numerous studies around the world which indicate that children carrying heavy day-packs is a considerable problem and may have potential long-term medical consequences. Back pain is a relatively common symptom among school children [22] and in many, the pain is recurrent or chronic even before puberty [23]. Studies have shown that school backpacks are felt to be heavy by 79% of children, to cause fatigue by 65.7%, and to cause back pain by 46.1% [24]. In addition, numerous studies have shown that in children, carrying weight in excess of 15% of one's body mass (which they almost always do), can lead to significant increase in trunk inclination [25], abnormal standing posture while carrying the load [26], as well as muscle soreness, back pain, numbness, and shoulder pain [27] and even spinal deformities [28].

Based on the forgoing explanation of the physics of load carrying with poles and the physical problems found in children, suspending the load would likely be helpful. A method to suspend loads in a compact package (i.e., suspended-load backpack) represents a potentially important contribution to solving this problem.

Tradeoff between electricity generation and reduction in shoulder forces. It also seems likely that when one extracts mechanical energy from the system and couples it to electrical energy conversion technology, that in effect, the load would be partially recoupled to the body. Hence there is likely a tradeoff between electrical energy generation and reduction in shoulder forces and this can only be determined empirically. Ultimately, the mode of operation of the device should be made adjustable, so that the level of energy generation (and thus coupling) vs. force reduction can be adjusted depending on the subjects' need.

Evaluation of Other Locations and Devices

Based on our analysis, using a suspended-load backpack to uncouple the load from the subject is likely the best location from which to extract mechanical energy and thus generate electrical energy. However, if carrying light loads, the mechanical energy which can be extracted is greatly reduced, thereby reducing the amount of electrical energy that can be generated. At the same light load, the reduction in force at the foot is more moderate, and hence under these conditions, the foot becomes a more attractive source of electricity generation. By building in a relatively small compliance and by using new materials (see Zhang et al., 2003, in this volume, [3]), this may greatly increase the electricity generation over what was obtained in the past. Although not as large as the energy obtained from the backpack, the foot may represent a useful supplemental position for electrical energy generation, and thus will be explored as well. By combining outputs from several anatomical positions, greater amounts of electricity can be generated over a greater range of circumstances.

Acknowledgments

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