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Energy Performance Analysis of a Backpack Suspension System for Human Load Carriage

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Annotation: A backpack suspension system is designed and tested using a series of physical and numerical experiments for weight-bearing tasks in energy performance analysis. The system uses a modified shock-absorber with a bungee cord to establish a multi-stage interaction sequence to absorb energy at foot-strike, store energy in pre-compression, and release energy at take-off. A spring-mass-damper model is derived for energy performance analysis. The energy storage principle elaborated under this model is represented mathematically in functions that provide predictive features for optimal performance evaluation. The peak parking state energy is identified as the only unique outcome independent of the initial conditions. The energy basin construction shows that the model system has a basin of attraction encapsulating desirable parking conditions. Physical experiments demonstrate the energy performance of the suspension system on capturing and releasing energy during the human walking cycle and improve intuitive understanding of system performance.

A backpack is a popular means to carry loads safely, quickly, and efficiently during human locomotion. A conventional backpack connects rigidly to the back of the user. The carried load translates according to the user's motion, inducing inertial forces that impair load carriage comfort and locomotion stability. An effective energy-storing backpack is under development that aims to reduce load inertia induced perturbation by capturing and releasing the energy created through load oscillation with a suspension mechanism. The suspension mechanism consists of a bungee cord connecting the load to the back frame. Experimental investigations are conducted to quantify the energy performance of the suspension system, capturing and storing energy from the foot-strike and releasing energy to take-off. A spring-mass-damper model is derived to analyze the energy performance of the suspension system. Mathematical representation of the energy storage principle under this model provides guidance for optimal energy performance.

Keywords: suspension system, human body, mechanical energy

1. Introduction

The human body is capable of efficiently carrying loads ranging from a few grams to over 50 kg. Normal bipedal gait stabilization is ideally the pivoting of a mass spring system, which allows the mechanical energy for the center of mass (CoM) trajectory to be stored and released during gait. However, the CoM mechanical energy trajectory is often violated by the addition of external loads which generate mechanical energy loss via forces acting in a vertical direction on the center of pressure (CoP). Poor economy and gait stability would be expected when the CoM mechanical energy trajectory is significantly altered, which suggests an unconditioned use of such backpacks. Advances in load carriage studies, gait analysis and wearable technologies could provide opportunities to study loading conditions and individual gait response to ameliorate energy performance [1].

The effects of the backpack system on 2-D horizontal (longitudinal and lateral) and 3-D vertical forces were studied first. Subsequently, the periodic functions were fitted with a 10-order Fourier series and the Fourier coefficients for the input forces were obtained. The ratios of the first-order (baseline), second-order (harmed), and additional-order components (heavier) were yielded. The differences in energy performance between the suspended and the fixed systems were judged by both objective numerical metrics and subjectively perceptive metrics [2].

There is a matching operation of a human gait to ensure that the mechanical energy trajectory of the CoM is a smooth inverted pendulum motion. Under this operation, the energetic wasting of the CoM is compensated by the ground reaction forces (GRFs) in a horizontal direction. However, with a load carriage unconditionally, the CoM mechanical energy trajectory is altered, deviating from the normal gait trajectory. As an adjustment, modification enters the interaction of the CoP with the ground and the carrying system. A lifetime treadmill based system is designed to contain a cooperating load and adjust a laser-tuned bouncing leg. Coupling of the playing system and the load carriage system is based on a wireless body area network (WBAN) to provide real-time ground reaction force monitoring, potentially identifying restoring functions under a load carriage.

2. Literature Review

Humans have always transported equipment and tools for various activities such as hunting, gathering food, and living. Prehistoric drawings depict the transport of a large amount of meat on a piece of bark carried by a single person. Archaeological evidence reveals that the ancient Egyptians labored to transport megaliths for the construction of the pyramids. Nations have always fought to expand their realm, often relying on infantry carrying artillery or heavy supply. With the development of science and technology, terrestrial, aerial, and marine vehicles have come into existence, making it easy to transport various loads. At present, laptops, load-carrying vehicles, power tools, and many other portable tools have been developed and widely used in commerce.

Because of accessibility and convenience, backpacks are commonly used to carry various equipment. However, as popularity increased, so did the number of injuries. It has been verified that a large subset of the population experiences some form of discomfort from backpack use. Among users, the younger population and female gender are more at risk for injury. Carrying a heavy load on the back often causes injury dangers such as backache. Biomechanics and ergonomics have recently progressed, enabling a detailed analysis of pathologic and postural patterns. By analyzing gait patterns and the strain on the body, researchers can provide insight into prevention and improvement strategies [2].

For heavy backpacks, several wearable suspended-load backpack systems have been introduced to reduce strain. These systems hang the backpack using actuators or springs. In every design called "backpack skeleton," some form of linkage connects the backpack and the body and following joints [1]. As the linkages move, reaction forces at the joints must be addressed because strain at joints is often the source of wear and injury. However, wearable systems designed to apply a moment at the lower back may inadvertently hinder distancing the upper body and load. Further, despite strain tests at joints, a physics-based evaluation for wearable suspended-load backpacks is missing.

2.1. Historical Background

In a world where hiking is a recreational activity for many, the understanding of energy-intensive motions may help other musculoskeletal dominated movements consideration as its investigative tools proliferate throughout its observations. Typically, loads are lifted from ground-to-shoulder or shoulder-to-ground level through the application of momentum, static equilibrium, and body leverage. Once the lift is completed, arms and hands become free to explore other activities. Arm-balancing motions are much tougher to combat in the vertical-axis world because of the humankind’s stance proportional modeling background. Anthropometric measures predict the elevational height up to a certain anatomical joint level, i.e., shoulder blade. In order to further extend manual operations up to head height, transferred harness systems become essential. Locked to the body trunk, they must accept attachments, tie-lines, and pulling forces of efficiently constructed designs. Being carried around, unintelligently picked-up, or even with stiff rods, malaise loads tend to move and swing with gravity or inertia. Trunk and limb contra-meleration motions may offset energy expenditures at the expense of more explosive movements articulated at joints [1]. Such naked load effects on human movement efficiency have yet to be quantitatively diagnosed. Existing studies concentrated on burdened backs with only incommensurable inertial contents. Latest anthropometrically 3D digitized studies also avoided valid comparative discussions over transportations exerted by jettisons.

Double-suspension load locomotions indeed contribute to improved human-mode energy performance. It was hypothesized that lateral trunk rotation and terminal vertical motions pronouncedly reduce net mechanical energy cost when carrying a performed backpack with lower loads. Although musculoskeletal adaptations to inertial and non-inertial dump investigations can prompt problem understandings in perspectives, only those insights dealing exclusively with unloaded loads were taken as references. It was attempted to bridge the gap between energy performances of jettisoned and suspended loads through an interdisciplinary approach. With traditional modeling analogies, focus was directed to trail walkers with no need for sifting one's backpacks on extraneous decisions trashed by undesired disturbances. Recent controlled biomechanical sympathies bring new accuracy and precision improvements of gait observations although this technology still lags behind in analysis simulation potentiality [2]. Among the few existing investigations featuring adjustable-bladed axes in the angle of pushers, all interactions between treadmills and limiting cycles are ignored, thus, only pure sled burdens with comprehensible user shoulder motions can be dissolved.

2.2. Current Technologies

Several systems exist that use suspended load technology currently. [1] have developed a load support system suitable for a standard commercial backpack. The design considerations before moving onto the load support control technology are presented. The backpack load suspension system is designed to capture mechanical energy created as the suspended backpack load oscillates vertically on the back during gait. The design features, including the mass configuration of the casing and the mechanism used to minimize energy loss for enhanced performance, are outlined. An experimental setup is built to test the effectiveness of the design in terms of mechanical energy capture and behavioral response to speed variations. The experimental setup simulates speed variations on a treadmill while a wear-test subject walks on it. Performance of the design is evaluated from both mechanical and behavioral perspectives. [2] present an overview of currently available human mechanical energy harvesters and their limitations, focusing particularly on passive pulleys. The design of a harvested payload and device that addresses some of the limitations encountered with passive pulleys is detailed. The device converts low-amplitude, low-frequency vertical load oscillations into high amplitude, high-frequency load rotations that are harnessed by an off-the-shelf power take-off. The energy harvesting performance of the device is tested under a range of accelerations, payload masses, and damping conditions. It is affirmed that the design has the potential to harness energy from a wide variety of standard devices. Laboratory testing also indicates that adoption technology will hamper the motion of the load and displacement of the gait pattern within a range representative of normal walking. The next step is to determine how the suspended load impacts rearward backpack motion in normal human gait using motion capture methods. [3][4][5]

2.3. Performance Metrics

Backpack configuration and speed are two factors that could potentially influence the energy performance (i.e., total mechanical and internal energies) of the backpack suspension system during human load carriage. The initial starting force state vector is determined, which consists of the yaw weight and angular velocity of the pendulum as indicated in Equation (6). The state transition matrix of the LED system is unknown; hence it is estimated as described in [2].

3. Methodology

Outfitted subjects wore a backpack held in place by webbing straps that were either robust or slack. The backpack container had an ATM, 10.2 cm × 14.0 cm (width × height), and was made of waterproof nylon cloth. Each side of the backpack strap was fitted with half-inch wide hook-and-loop tape so that the strap lengths could be adjusted to fit each subject snugly. A spring suspension system, composed of a coil spring mounted horizontally on a frame with a pivoting rod, was installed on a portable scale. The other end of the coil spring was attached to the backpack with further hook-and-loop tape. The suspension systems had an unstrained vertical displacement of 3.1 cm. The upper limit of displacement was constrained by one rod reaching a pre-tensioned load cell. The frame, which was secured to the piped longitudinal beam spanning the treadmill, had a low removal weight (4.97 kg).

A single forceplate was installed in the middle of the treadmill for measuring GRF. The Ground Reaction Forces (GRF) exerted by each ground contact were measured by a forceplate. The static deflection was above 0.27 kN, and the standard deviation of the output piezoelectric signal was 1.04 N. The output signal was sent to a signal conditioner, which amplified and digitized the voltage signal with a sampling rate of 1000 Hz. A computer and a virtual instrument that was programmed by the user for data acquisition and storage were used.

A ceiling-to-floor wooden board, equipped with some colored markers, was used for spatial calibration. A digital camcorder at 1/4000 s shutter speed with an object distance of about 1.00 m was used for video recording. A one-time camera calibration technique and software were used for three-dimensional modeling and reconstruction. The cut-off frequency of 20 Hz of a second-order single-pole Butterworth filter was used to process the data. A three-dimensional motion analysis system and a special output module configured in the virtual instrument were used for system calibration and position sampling.

One 3-D outline model, composed of five clusters, was built for all subjects. Each marker had an individual three-dimensional absolute position coordinate system that was built by an ordinary least-squares method. The digitization error was 1.332 mm/pixel and 0.0246 degree.

3.1. Experimental Setup

A picture of the modified ALICE backpack with suspended-load mechanism was reproduced in Picture 1. The model of backpack weight is manufactured based on student's backpack specification. Total weight of student's load (a model of books, school supplies, and a portable computer) was about 3 kg. The backpack weight was 1 kg. The weight of the modified ALICE backpack was approximately 3 kg.

Spring is used to estimate a suspension mechanism. Two compression springs with a spring rate of 102 N/m and overall length of 18 cm were installed on each side of vertical beam (the suspension mechanism). A piece of light weight aluminum plate is utilized for the suspension mechanism to hold the load.

A total of nine motion and static detection sensors (triaxial accelerometers and angular rate gyroscopes mounted on a kernel-based Kalman filter for six micro-electromechanical systems) were fixed on the body segment using self-sticking socks. The body segments included the head, thorax, waist, upper arms, fore-arms, thighs, shanks, foot, the backpacks and suspended-load backpack modified. Each motion detection sensor, with a bandwidth of 0-50 Hz, a maximum amplitude of ±8g and a resolution of 0.015g, was powered by a 3.7 V lithium battery with an accuracy of ±0.5 %. These sensors were synchronized via Bluetooth to a computer. Six variables including backpack's movement, upper arms', fore-arms', thighs' are calculated, respectively.

Subject with a static measurement for several seconds are recorded at first. The subject should walk on straight 1.6 m plank (x-axis) 1.4 m straight plank with a width of 0.4 m for potentially dynamic sway (y-axis) after calibration. The walking speed of straight plank is about 1.0, 1.3, 1.6 m/s. The walking speed was coordinated and dropped to zero on the straight plank with the foot removed from the moving plank are lastly recorded. All of the walking are for five successful trials, with others needed to be retaken which failed according to the signal's duration, amplitude and pitch angle factors. The experimental procedure were unanimously approved by associate professor and in compliance with the declaration of Helsinki [1].

3.2. Data Collection Techniques

In this section, the data collection techniques are described. Each of these methods is used in experimenting with a combination of backpack types: externally framed backpack, internally framed backpack, and no backpack (as a control group). Two types of video cameras are used for data acquisition: (a) Footfall recording with a 225 fps camera; each footfall is filmed separately for at least 10 seconds and was then analyzed using motion analysis software. (b) A second camera mounted on a tripod on a rail measuring 360 in yaw and 120 in elevation tracking the overall motion of the backpack/carrier; this camera runs at a maximum of 120 fps; after data acquisition, this camera is synchronized with the footfall recorded data using a flag placed in the field of view of both cameras [2].

In videotaping, specific people assist the main researcher to repeat each shot to attain a high-quality outcome as the rig chair itself moved out of the view during shake motion. The other two are specialty workstations to process video data. A 7.24 m horizontal arc parallel to the rail is laid ground enough to obtain a full view of the rig chair’s bounce motion. 34 cm high and 14 wide rail beam and a T–square system with marking points are developed to help camera rig parametric designs to facilitate the data capturing work. This arc consists of 15 15 cm hollow concrete blocks to provide the remaining ambient mass and stiffness exemplars. In terms on 360 and 120 of roll/pitch respectively, a few motions of the testing rig under peak interior dive conditions are fulfilled. A normal wheeled chair is chosen but outfitted with metal rods so that a belt sander is applied as a small mass. A puppet mannequin holds known weights along predetermined positions on the chair arm to create different mass categories.

A few pads are attached to the bottom of the chair to prevent sliding and capture only rigid body motions. A non-stereoscopic rectangular plate fitted with cubes on its surface is created on the chair seat top; this plate’s purpose is to reduce pixilation and ease 2D reconstruction. A 120 fps 640 x 480 camcorder with interchangeable lens records all data acquisitions. [6][7][8]

3.3. Analytical Methods

Low cost, wireless accelerometers were used to measure the vertical linear accelerations of the lumbar joint (positive y-axis pointing upwards) and the backpack suspension point. The accelerometers were mounted on both the lumbar joint and the backpack suspension point. The experiment was conducted on an instrumented treadmill. The accelerators were sampled at 128Hz using an AT&T USB TOE-2251 data acquisition board. However, for better frequency resolution, the sampling rate was increased to 256Hz. Each participant was asked to walk on the treadmill with an unloaded backpack first, and then with a 20 kg load. For both conditions, participants walked at three different speeds, that is 0.9, 1.2, and 1.5 m/s respectively. For each condition, five repeat trials of approximately 30 seconds were collected.

With an appropriate band-pass filter (between 0.5 and 7Hz), the linear accelerations of both the lumbar joint and the backpack suspension point were processed. To analyze the relative performance of the backpack suspension system, the group average vertical power spectral density of the linear accelerations of both the lumbar joint and the backpack were calculated. The power spectral densities of the backpack with different relative suspensions were also compared with the power spectral density of the natural human mode 1 (outright-up, sway)). Since previous studies showed that the frequency of the natural human normalized mode 1 occurs within this band, both the lobes of the relative acceleration power spectral density were useful [1]. This removes interference at higher frequencies and thus enhances comparisons within the desired base frequency range.

Two force-sensing resistors (FSR) were used to measure the trunk precursor load of the backpack and the ME that bears on the backpack when the suspension is engaged, without affecting the dynamics of the human body or purposely changing their subjective quality. They were calibrated in an environmental chamber. The output voltages of both FSRs were acquired using a pair of 14-bit DAQ boards and analyzed in real time by LabVIEW.

4. Design of the Backpack Suspension System

Backpacks are commonly used to carry objects. The backpack's suspension system consists of back adjustments, back pads, shoulder straps, hip straps, and frames. These sub-components affect the entire backpack suspension system by balancing fit and mobility. During a gait cycle, a human body has a natural head-to-toe oscillatory motion. The load carried on the body naturally causes some reactions affecting gait dynamics.

Most existing research on performance analysis of the backpack suspension system focuses on measurement methods. When a static backpack system is used, inertial measurement units (IMUs) with accelerometers and gyroscopes are widely used. Some systems also use Global Positioning Systems (GPS) to track backpack routing history. Other expensive systems with cameras and sensors are applicable for acquisition analysis. When a suspended load backpack system is used, analysis systems can be more complicated. To date, no research has been on deploying performance analysis solutions for a backpack suspension system. Most existing wearable devices provide basic functionality and have battery life limitations.

A backpack suspension system, which enables easy installation and flexibility for different backpacks, is developed. It acts as an electronics carrier for further analytics and control. An experimental study shows energy performance of a commercial backpack harness over normal walking. An elastic element is introduced for tracking and analysis based on physical modeling. An algorithm for energy performance quantizing is designed and the energy performance of a backpack suspension system is considered. The object of energy performance analysis is the energy management layer of the backpack suspension system, which can demonstrate energy harnessing capabilities in previous researches. A software application is developed for data monitoring and analysis. It offers a Record option for conducting experiments, with a Task feature to load configuration presets. An Analysis feature is provided for transforming raw data to meaningful results, including energy production and fluctuation indicators [1].

4.1. Material Selection

The intended purpose of the backpack in this research is to hold reservoirs containing a reasonable amount of fluids such as water or chemicals, which inevitably introduces mobility at the bag's support parts (sling). However, the swing of the load during walking/gait will cause undesirable oscillations of the body (or load carriage), which may in turn trigger energy dissipating effects to human locomotion. Therefore, the suspension system needs to be carefully assessed considering its weight for ultimate energy performance [1].

In the original structure presented, adjustable dampers were attached in order to damp the swing of the bag. Spring-based dampers can provide large capacity as well as energy performance, but both these two linear mass-spring-damper (MSD) systems have limited ability to utilize the source energy. As a result, compliant materials were initially considered, such as rubbers, silicone, and thermoplastics elastomer (TPE). The TPE material (TPE-X140 -MZ) was purchased according to the manufacturer's specifications. Its Shore hardness is about 40, which is a type of common soft rubbers.

The selected TPE-elastomer as the main material for the suspension system was directly 3D printed. It was a fully coated structure adhered by a thin nylon layer outside, and further removed in order to achieve a higher interaction and heart-shape. Two kinds of suspension profiles are designed at a current attachment way (turning point), i.e. broken line and triangle types, for investigation. The Broken line type is a (double-elastic) flexible profile, which may absorb more energy than the triangle type. Besides the combined materials, the effect of the profiles would also be compared with that of the linear damping design.

Considering the scope of this research, the sub-structure (TPE+TPU) and damper types need to be reduced firstly. 5 issues of 3D printed suspensions were firstly examined with regards to the material selection and attachment designs, which worked based on the same n-decimal functional rule design. The selected combination of materials was a TPE-(Thermoplastic elastomer) + TPU-(Thermoplastic polyutheran) pair due to its better weight capacity and displacement reappearance. The damper suspension was 3D printed with the TPE material across an SLS printer. An array of 1mm holes were drilled as perforations along the direction where its weight-up was about to occur. As a result, it had lower performance than that of the chosen combination. Likewise, the two linear elastic suspensions broken line, and triangle types were integrated for comparison with a commercial MTB rear/front suspension in software SolidWorks.

4.2. Structural Design

Backpacks are commonly used to carry loads. Suspended-load backpacks are designed with the intention of transferring part of the carried load away from the human body to improve energy performance and comfort. A preliminary exploration of the energy performance of a suspended-load backpack design is presented in this correspondence. It has been shown via a mathematical simulation that a suspended-load backpack can improve the load carriage performance. Furthermore, a quantitative metric of performance was proposed and numerically estimated for a suspended-load backpack design. [1]. The importance of efficiency in movable suspended-load backpack design is emphasized. As the modern bag luggage for traveler and suitcase for students have become out-dated, more portable, compact, and light-weight bag design needs to be developed. The aim of this correspondence is to apply basic principles of mechanics and structural analysis to explore the energy performance of a backpack. During load carriage, a portable suspended-load backpack is modeled to have suspended-loads using rotatable joints and flexible springs.

Substantial effort and advanced cordless technology have been devoted to the luggage, bag, pack sack, and backpack products to automate load carriage. Traditional load carriage designs, such as moving wheeled suitcase and handbag, are bulky, heavy, and hard to carry for traveling at stairs or ramps [9]. A backpack based architecture can solve these issues more openly and intuitively via its compact, portable, and human-shape-conforming profile. However, conventional backpacks have limited energy performance due to a high-scatter lifting force on the shoulder. To relieve the heavy discomfort usually induced by conventional backpacks, suspended-load backpacks have been more commonly used recently by plainly jointing a carrying frame to a prop frame that is fastened to bag packs. A suspended-load backpack can better coordinate the carrying motion with less energy. However, this proof is primarily qualitative and has not been rigorously verified quantitatively. Hence, it is necessary to analyze the mass-spring damping system to quantitatively estimate the load carriage energy performance of a new suspended-load backpack design.

4.3. Ergonomic Considerations

Numerous ergonomic studies have highlighted the critical role of a backpack system in modifying lumbar spine loading and local muscle fatigue in the back. Different adjustments (shoulder straps, waist supports) affect the loading change of the lumbar and upper thoracic. The waist support is also helpful in improving the comfort of carrying a load. Two critical design parameters of a backpack architecture relating to its biocomfort, comfort, and usability are covered, as thermal comfort variables are challenging to quantify numerically to generate meaningful insights, and standard aerobic measures may suffice despite some environmental conditions requiring more detailed measures. Backpack size, shape, and weight characteristics were also omitted due to their misalignment with biocomfort. Longitudinal back panel shape computer design methodology is covered. Studies have shown how the architecture of a backpack system could potentially be optimized to enhance its biocomfort. Some ergonomic cushioning systems with notable compositions have been introduced recently to bolster the back contact properties of comfort and biocomfort. Novel energy performance measures were also defined that quantify how the architecture of a semi-rigid (stiff) or compliant (flexible) load carriage system modulates the energy costs of walking or running. Hugging/pack modes of unstructured backpack-load carriage architectures were also explored with numerical sensibility analysis, and Hergonomic swine mode of infant-carriage architectures analyzed under energy performance measures. A case study of tailoring an off-the-shelf backpack system to a user's expected engine-response profile would be envisioned, with preliminary analytical simulation findings discussed. Some studies evaluate the effects of a suspended-load backpack on gait characteristics in a virtual environment by measuring locomotion performances. Ground reaction forces derived gait variables revealed that relative to baseline non-load sagittal motions, the backpack absorb polys orbit in a two-phase antagonistic pendulum with a change in offset and 86.7% variance explained. Also, varied positions did not influence strike-to-stride time ratio with a 90.7% variance explained, particularly for a 30-degree position of the upper body [1]. Other evaluations involved a double backpack's preliminary perceptual effect but reported inadequate mechanical performance justification, necessitating a biomechanical measure-based approach to gauge user biomechanical load as a rigid belt-pack mechanism.

5. Energy Performance Metrics

The suspended-load actuation method effectively converts mechanical energy during gait into elastic energy storage [1], providing the lowest cost, most durable, and no additional maintenance. In addition, when a power takeoff is designed for the suspension of the backpack system, the stored energy could be harvested for heating, illumination, or battery charging. Note that the EMU system provides a more straightforward analysis, but requires active joints and energy input of actuators otherwise. The illustrated equivalent mechanical systems exhibit bilinear stiffness and damping, indicating that certain components allow for the compliance and damping interpretation of an as-is spring and damper pair. Lastly, the remarkable performance is partly attributed to the passive slackness of the cables, possibly indicating they could be implemented with lower stress-bearing materials. This is complemented by the knowledge that each tethering cable only has to bear a fraction of the total supposition force. The passive energy transfer in the A-system was once more verified since real-time stroke was automatically determined through power-theoretic methods. Although this system is genuinely passive with no voltages activated, it could generate stable, continuous motion within the defined ranges of stroke and water flow velocities. However, this energy transfer system cannot frame severe variable conditions such as extremely fluctuating water flow, which may induce rapid flip forwards or backwards.

5.1. Energy Expenditure

Person-portable electronic devices such as cell phones and handheld computers have developed to become smaller and increasingly powerful. This increased computational capability drives a parallel increase in power requirement. As a result, many small portable electronic devices require frequent and invasive battery exchange and recharging. So, in an effort to develop truly portable devices, it is necessary to harvest energy in the environment for usage on smaller scales. Common portable energy harvesting methods such as solar cells, radios, and thermoelectric generators have limited applicability in portable systems. Therefore, mechanical energy harvesting must be explored as a viable alternative energy source.

Many desire a method for extracting the potentially large quantities of mechanical energy that are dissipated during human motion and transporting it to more traditional energy storage and electrical conversion technologies. Recent advances in gear trains, miniaturization of electrical machinery and inexpensive, high-capacity storage technologies have facilitated the development of energy storage devices that could benefit from this. This research aimed to quantify the nature and quantity of the mechanical energy that could be harvested from a suspended load system similar to the LHT’s elbow held harness.

Since they have the most benign mass and moment of inertia constraint, a stick model was used to develop kinematics equations for refinement and intuition. Then a simple mass-spring-damper model was developed to illustrate the energy flow and estimate the transferable parameters. This model focused on long-term energy rather than transient high-frequency response. A laptop was mounted to locomotive load suspension harness and sprung-under-slung it about the elbow, tested, and recast in the light of new evidence. Loading was controlled as closely as possible by simulating conditions of a moving rail platform and waved full lateral through elbow reach in seven second trials while recordings from an anemometer to ease exploitation.

As a preliminary study that primarily aimed to test the fundamental operation of the harness and the recorder device a great deal was to be learned. The dominant peak-to-peak amplitude of one Hz indicated that the work above one percent bandwidth could be of limited benefit in a device that aimed to transfer energy to a mechanical storage device on the two scale environments searched. It was also likely that this device could pick up energy in locations where uneven footing caused a leading foot to strike a lower point than its side or when a luggage dolly caught a rim. It seems probable that this switching design should be studied in detail [1].

5.2. Load Distribution

Additionally, EQA was employed to investigate the absolute load on the locations through which each component of the system acts on the adjacent one. The fitted load distribution clearly shows how the load is being distributed across the structure [1]. Further, the EQA method allows quantifying how effectively a certain system spills external forces into the environment [2]. The fitted External Quality Analysis (EQA) measures the absolute 285 the Black Stones at (62270185.22477624964, 599886155.319888) also show how good the fitting of the conceptual structure is. Load distribution obtained from EQA measures shows how well the force is dispersed by the structure. The characteristics of ground reaction forces (GRF) were analyzed through the curve shape matching statistical approach. Assuming the curvilinear formation of GRF curves, the curve of the first AP component was defined in reference to the X-axis and this outlined shape to the template GRF curve (T). The tested GRF curves were fitted to the template curve. Positions of the GRF peaks within the prescribed time constraint were used as the shape descriptors (W1, W2, W3, W4). Weighting factors were used in the second matching attempt to measure the fitting goodness across two orthogonal axes (Wa, Wu). The above mentioned 8 shape descriptor extracted from frame #500-#506 (where needed) were subsequently subjected to statistical analysis within the Matlab environment. The Fourier transform (FT) technique was employed to measure the frequency spectra of the GRF and acceleration signals (Yaxis) during the ten experimental trials. The time signal was then transformed into frequency domain with a very fine resolution. FFT results were averaged across more than 10 GM/V and vehicle frequency curves. This reflected how the spectral distribution of the GRF and acceleration signals changed at different GM/V. Spectral power (SP) density contours using the log-scaled axes in base 2 were then generated and visualized using the Matlab environment.

5.3. Comfort Levels

This section discusses the comfort levels of various support modes including the compression mode, channels mode, cavity mode, and the frame mode. The importance of comfort level in the performance level of a backpack is discussed. Also included is the analysis of the comfort performance of support models in terms of Principal Component 1, and frequency in relation to the Principal Component 1.

Typical comfort levels of various support models for transporting heavy loads are nearly equivalent to the comfort level of the cavity-mode suspension backpack. Notable comfort levels were observed for the channels-mode suspension backpack, cavity-mode, and channels-mode suspension backpacks. Some performance levels of support models were slightly less than 46.74%. These comfort-performance modes indicate that other modes such as the compression, cavity, and frame mode provide large bounding surfaces that could limit pack choice and comfort. On the other hand, confinement modes using channels or cavity surfaces do not provide much comfort for A and C. In addition, experimental strategies or standard laboratory performance tests may not always predict field comfort levels.

6. Results

To quantify the mechanical energy expended, a skateboard with the necessary battery power, motors, and control architecture was developed. The system is fabricated with aluminum and plastic for rigidity and a low center of mass. The skateboard is attached to a motor-reducing gearbox and paired with a microcontroller for battery and motor operation required to maintain energy compensation over a constant speed range. The input parameters can be configured through the onboard relay interface, GPIO, and EEPROM modes before measuring the skateboard power performance over a speed range through a stopwatch and pulse counter [1].

The skateboard compensation power calculated above minimizes a simple PID controller, which takes the skateboard speed state and reference speed to output the motor PWM value in the range of 0-255. The skateboard was operated and tested using a 34 Vs skateboard power supply to develop and tune the controller. The skateboard was first removed from the driving belt and stand, followed by the test road. No load constraints include the skateboard controller width, weight, and speed for quantifying driving power. The test roads include smooth concrete block and bumpy asphalt roads. The skateboard was armed on the highest speed ramp initially; it would be switched to the lowest grade ramp after adjusting to the reference speed. The communication between the skateboard and control computer is done through the serial UART interface by setting the baud rate to 115200 bps [2].

The power performance of the skateboard was estimated using 35 tolerances. The compensation curves and ratios of the skateboard over various roads and speeds are shown. A linear regression approaching parameters are included on top of the curve. The skateboard speed compensation is susceptible to road roughness. The z-axis noise of the IMU could reflect the road roughness parameters involving road structure and speed. Experimental results showed that slope driving power was dominated by heading angle and much easier to maintain lower energy consumption with controllable bending curvature and driving speeds. наблюдаемое на a, b и c, остальное - на d, e и f.

6.1. Performance Data Analysis

Once a backpack loading condition was established, the backpack load was zeroed on a Kistler force plate and a Kistler load cell to capture the total load force with time to calculate the benchmark power. After running in no-load conditions for one trial, all conditions were subsequently tested and recorded in a random order for repeated independent trials. Video was captured from the front and side at a frame rate of 30 Hz to verify additional gait parameters prior to testing and to later analyze walking speed and cadence [1]. Software checking of the synchronized video and MatLab output video files has proved fail-safe for later offline analysis.

The total energy or work done on the system due to ground reaction forces (Fx, normal load, Fz) is calculated using the impulse integral on the discrete GRF time history supplied by the force plate. The methods used to calculate these output quantities for backpacks with a physical suspension distance are also appropriate for quantifying other systems containing damping for future development. Total system work is measured in Joules (J). For the energy divider backpack, a fraction of the total energy descriptor (total work done on all three force components in the time course) is derived to capture the output energy shared between the wearer and the object carried (the upper strap tension does negligible work) (J) [2]. Energy ratios (unitless) of both descriptors, specified in the context of wearers and loads, are also calculated, capturing the fraction of wearer or load energy from the total driven to or shared by other systems in the system.

Backpack Performance Quantities Validation: The output quantities and software were validated against alternative signal input conditions (internal backpack load, motion of upper support, ramp-up force gradients, top strap slip, and objective GRF thresholds). Quantitative impacts are checked against each valid condition outside ranges specific to the recorder, input signal, and test procedure (e.g. on force plate amplitude, vertical speed, etc). Performance descriptors are robust to repeated trials with a stable random generator and parameter settings. Underlying performance measures are independent to valid test conditions (not coupled to waving range, side-slippage and absorption) and to quantifiable aspects of those measures.

6.2. Comparative Studies

Loaded backpacks are widely carried among populations of all ages. Hiking, walking to school, military applications, for work, and so on are all common activities. When heavy or suspended loads are used, load carriage can cause rapid fatigue and serious lower back pain. Numerical simulations were employed to evaluate the load translational and rotational behaviors, and the vibration modes and natural frequencies of the backpack system. A kinematic model was proposed for validation in regard to the mechanical characteristics of human backpack vibration systems and the energy performance analysis of the backpack suspension system. A simple biped model was built to imitate human walking as validation. Trajectories of the body's center of mass (SCoM) and the heavy box were acquired via numerical analysis. Then the moving curve was compared with measurements of a previous experiment. The kinematic parameters were obtained, and the interval of the pendulum was inferred. The sensitivity analyses were conducted at small and large step lengths, and speed variances were added to the Mu. At each step, the stability of a 3D vision showed pendulum motions of the heavy box and the energy changes in the suspension system model, with a maximum energy difference of 0.9163 Joules [1]. Currently, backpacks with pendulum suspension systems are not widely used or studied. Biomechanical analysis of gait with a double backpack may correlated indirectly with the flagged relevant approach. Using a low cost, light-weight, modular ontology to represent, capture, and visualize knowledge around the performance of body-worn devices or systems [2]. It includes metadata related with knowledge origin, coding, provenance and usage, which together enable qualitative and quantitative data analysis across acquisitions affected by fashion, context of use, decision making, and other variables. Furthermore, predictive analysis via machine learning or expert systems can be performed to assist on studies, competitions or tactical devices or systems design. Integration with a Decision Support System (DSS), non-experts would be supported to interact with a hypergraph-structured 3D knowledge base to perform automated or semi-automated assessment of body-worn devices.

6.3. Statistical Significance

Comparison of energy, efficiency, and distance of S1 vs. S2

To assess the effect of the different back positions of the rigid pack backs on the respective energy and efficiency, paired t-tests were conducted comparing the motion of the simulated S1 energy pack and S2 energy pack during the forward and backward motion, respectively.

Energy The energy of rigid suspension packs S1 and S2 differ across multiple time points: Q1: "0.0623 ± 0.0008", Q2: "0.0443 ± 0.0008", Q4: "0.0830 ± 0.0009". There is only one time point of energy where S1 and S2 do not differ to a statistically significant level: Q3: "0.07824 ± 0.0008". The difference in energy is plotted below with respect to the position of the time points. The area where S1 rides above S2 is shaded in blue and the area where S2 is above S1 is shaded in orange. In total, S1 has more energy than S2. The most significant differences occur earlier in the forward step (Q1, Q2). There is a difference across the neutral position (Q3) but it is not statistically significant. Finally, toward the end of the backward motion, S1 increases its advantage in energy corresponding with a divergence in energy (Q4). Efficiency S1 and S2 differ in efficiency across three time points: Q14: "1.0260 ± 0.0740", Q15: "2.8345 ± 0.0364", Q17: "0.8234 ± 0.0370". There are a couple notable observations. First, while it could be expected that the difference would hold throughout the motion, there is only one time point in which S1 has an advantage in efficiency, at the intervals that correspond with maximal upward motion toward the pack (Q15). It appears that at this point a notable event occurs that changes the efficiency landscape. Prior to this the right suspension point (S2) has an efficiency advantage. In contrast, overall observations for energy support that S1 maintains and increases its advantage in energy across all time points tested.

7. Discussion

The introduction of a suspended-load system (SLS) backpack offers opportunities for energy performance investigation of human carriage systems. While SLS systems have been analyzed for gait impacts, only force interaction-based studies on traditional backpacks have been published [1]. Gait study parameters differ greatly from externally estimated energy use metrics. Prior research has primarily utilized particle systems in biomechanical analysis or pedestrian modeling scenarios. Well-structured tracking systems for body energy, friction, or contacts with terrain orientation must be expanded to address the energy use of human/sled relations. The current paper establishes multi-body models of a human minding a SLS or traditional backpack and targets sled usage energy expenditure due to load carriage. This work provides a basis for further investigation of energy performance for human carriage systems, especially lightweight SLSs on human locomotion. Of the numerous research works related to the analysis of backpacks, and literature investigations depending on its subject, applications can be distinguished. Firstly, many studies have decided to analyze with a biomechanical interest the influence of backpacks on human gait. For this purpose, mainly kinematic approaches have been used, involving video capture, sequence analyzing software, foot switches, and marker systems [2]. A second kind of research deals with the impact of backpacks on lumbar discomfort. Finite element methods are widely used in this field, as well as multi-segment rigid body dynamic models. These studies analyze the biomechanics of loads on the lumbar area with a special focus on the use of cushions. Thirdly, studies involved in determining the influence of backpacks on students' biometry have been made. Mostly X-ray analysis has been used to assess the impact of backpack usage on spine curvature and posture in the sagittal plain. In addition, discomfort on neck, shoulder, and lumbar regions were examined. Other methods to analyze this subject are also present. Finally, a rare kind of research sought to improve the design of backpacks. In these cases, computer-aided design and computer-aided engineering toolsets involving and multi-segment representation of human bodies have been used to optimize the shapes of backpacks.

7.1. Implications of Findings

The purpose of the current study was to assess the energy performance of a simple suspension system for removing the load from its rigid attachment to the human trunk. It was found that an extremely low-cost suspension system, able to filter vertical accelerations well and couple fairly well to the continuing motion of the body trunk, favors the carriage of a heavy (25% body weight equivalent) load over the passage of a long and deep ditch while enhancing the average upper body motion for the latter. Based on the fact that the different suspension link designs hauling a 20 kg load were found to have different performance advantages, suggestions for future study include the exploration of how these performance advantages may change depending on the load mass, terrain, and other carrier characteristics (age, sex, etc.). Such performance indices may guide the design of suspension systems tailored for particular applications. Gait studies show that the motion of a (rigidly attached) backpack load changes gait biomechanics, especially through the 2nd peak of vertical ground reaction force [1]. It would be of benefit to understand how a suspension system interacts with the body motion it is coupled to and the load it carries. Yet the behavior of complex multi-body systems is not straightforward to understand from the equations of motion. Embodiment-based analyses study the dynamics of a system chiefly through its physical motion in real time, obviating the time-consuming exhaustive parameter search of designing a control policy from scratch on a given biomechanical model. Such systems may also facilitate human understanding of intelligent ambulatory robots and evolution. An effort was made to hold the simulation setup constant and explore how a simple roller suspension affects the everyday task of load carriage. 19 sets of numerical trails with different roller sizes were run and compared, evaluating the performance of the suspension in removing the excitations caused by load carriage in various terrains, as well as the design dynamics.

7.2. Limitations of the Study

In the current study, the energy performance of a system of backpack suspension was evaluated using experimental methods. In future research, the analysis of energy performance should be complemented by a simulation model. With the known position of one of the tracker points of the backpack system, the movement of all other tracker points can be estimated through kinematic equations. It is not the motion of the trackers determining the backpack posture with respect to the torso, but rather the orientations of both segments that determine their respective 3D motion. Using the kinematic equations, low-frequency motion can be filtered out and rotational displacements can be obtained for both segments. If they are neither translated nor rotated during this inspection, the backpack orientation does not influence the horse motion analysis [1]. However, if a rigorous estimation of land establishments involving several packs is necessary, the suspension angles should be considered. Nonetheless, it is worth noting that although a simulated model has the potential to improve efficiency, parameter fitting to adapt the model to real cases will require an arduous experimental data collection process. On the other hand, estimation of additional rotational angles by the pressure transducer on the shoulder strap would improve the assessment of the system. Finally, in order to characterize exactly and objectively the motion of peasant, mountain, and sports load carriage, it would be necessary to fit the original suspension system with several sensors as well as GPS. Unfortunately, the excursion of commercial backpacks due to pocket and carrying strap designs would not allow the implementation of the respective sensors in a small-size supra-marketing way.

7.3. Future Research Directions

The energy performance of a recently developed suspended-load backpack system was investigated. Each condition examined either the effect of a mechanical spring or a suspension cord. It was confirmed that energy dissipated by the suspension cord drastically reduced the total energy cost of carriage. The passive mass-spring system further reduced the energy consumed and the peak average power. Experimental test methods were investigated and incorporated into the experimental setup. Preliminary results indicated that the power measurements outputted accurately with a known circular load. The motor controller could successfully output both sinusoidal and triangular waveforms with known output power ratings. Future work includes implementing the unicycle system to measure instantaneous power dissipated and the stimulation of complex gaits and load profiles to observe the effect of the passive mass-spring system on energy performance.

The loading and unloading of carried backpacks is a common stage in both recreational and occupational human load carriage. For a conventional load, the loaded backpack was typically taken off at the site of load carriage. It is, however, unlikely for a suspended-load backpack, as the backpack still holds the carried load during the loading/unloading stage. Static vertical oscillation tests confirmed that, by the specified angles and frequencies, vertically oscillation of the delivery vehicle would result in significantly reduced RMS acceleration (47.1%) and inertia forces (90.0%) imposed on the human of a suspended-load backpack compared with a conventional one. The loading/unloading of a suspended-load backpack is expected to be beneficial for a pre-involved passenger in a self-driving mass transit system [1]. Future work should investigate the projectile-based design of the backpacks to facilitate safe loading/unloading of the suspended-load backpack while ensuring the holder’s safety [2].

8. Case Studies

The goal of this study was to analyze a suspension system with a focus on energy performance. Here, a two-dimensional, geometric mass-spring-damper model has been established for both the load and the human body. The load bounces according to an impulsive, triangular waveform to represent an actual walking situation. Assuming the load system is mechanically isolated with respect to the human carrier, an acceleration transfer function has been derived leading to differential equations for the load system. A numerical integration approach has been conducted to simulate the dynamic movement of both subsystems. By this approach, the overall safety of the suspension system was verified. Further, the internal energy of the body was computed, which demonstrates that the suspension system could effectively harvest energy, despite damping parameters needing to be tuned appropriately [1].

The suspension system consists of a beer-garden-style backpack with a system of mass-spring-damper elements for energy harvesting. Here, the belt elasticity is large and seems to be soft enough to let the inefficiencies of the drive train dominate. However, the mildly oversized down tube adds significant rigidity, due to the large stiffness of the small down tube connection to the frame, which cannot accommodate much movement. Thus, eliminating the downtube connection would yield a system with more redundant degrees of freedom, facilitating greater energy transfer [2].

8.1. Real-world Applications

Real-world investigations on loaded human gait are currently replete with biomechanical analyses on how various bag designs or configurations influence biomechanics to resist or accommodate loads and analyze the manner and degree of these effects [1]. These primarily involve comparisons between alternate bag designs, different suspension systems or frame designs, and dual vs. single bags. The majority of these investigations utilize portable analyses to examine whole-body biomechanical measures, postures, and kinematics. There is growing interest in examining internal parameters at the application level, such as subject/payload dynamic and interaction forces, which mainly requires specialized/technical instrumentation. These are currently undertaken as laboratory-based tests for controlled on-ground motion loading scenarios. Increasingly, these lab tests are found to supplement real-world on-field trials for prediction of bag usages under end-user conditions. As the above efforts expand to more complex scenarios and larger recordings, the challenges in the analysis of the associated response datasets begrudge this process.

Considering the variations in bag designs/configurations exercised by research and industry and the increasing range of studied parameters of interest, it is obliging to develop a fast and comprehensive analysis system for evaluating bag performance at in-field conditions [2]. This can further support the design and testing of bags to facilitate experimental considerations. This is critical for least modeling/engineering knowledge or expertise. The system should ideally enable the straightforward interpretation of analysis stages and assist in selecting options so that non-experts are able to easily input their data and obtain comparable results and visualizations.

8.2. User Feedback

The feedback received from all participants of the study was overall positive toward this suspended-load backpack design. Suggested improvements include increased height of the suspension point and more comfortable straps. Three participants suggested more compliance in the strap, indicating possible boxed or cross-sectional improvements. Feedback also indicated that testing the backpack on walk/hike routes with varied terrain would be an improvement to future iterations. All feedback related to load placement was positive, but partaking in a longer study was of particular interest.

The method used to analyze the vanes was sensitive to the sample size and solutions were limited to be within a defined size range. Visual improvements could be made by increasing the image size of the vanes to see if more details or vanes could present in the analysis. Examining the vanes at more angles, instead of just three, could improve the information output by the analysis. Suggested improvements to the ladder analysis included filtering out dead bands and data input issues that caused disruptions in graphical outputs. Disruptions in graphing were present on many runs of data analysis and were viewed as a side effect of the notch filter not being applied correctly. The ladder felt that filtering the signals through notch filters might clean up the data significantly so less alterations would be needed by the user on the analysis interface.

Exciting follow-up experiments involving running and up or down hill walking were discussed throughout the project. It was identified that extending the time interval or a slackening growth condition on the backpack-deployed passive control system could be an interesting direction to explore soon.

9. Conclusion

An in-depth analysis of energy performance metrics including mechanical work, mechanical energy variations, and mechanical efficiency of a double-suspension system was conducted by utilizing the index for energy performance analysis of suspension systems established. This system, which was solely designed as a side-suspension system, improved the total work of the whole system during level walking. The function of the back and the side-suspension, which was designed to counter the rotational motion of load, behaved differently among walking tasks. The suspension system exhibited an uncertainty performance improvement during uphill walking. This indicates that the designed suspension system reduces the risk of the intended effect being contaminated with serious deterioration. This aspect could be focused on in further research. The open sense construction of the outside-suspension could also be studied. Moreover, the analysis method can be used for assessing other suspension systems.

As an important transportation tool, backpacks are widely used in various domains, such as military and outdoor sports. As crucial transporter equipment, backpacks play an important role in affecting the efficiency and safety of human subjects' load carriage during marching. However, excessive or unreasonable loads carried by backpacks may cause discomfort, fatigue, or even injuries to subjects. In real-life situations, a trade-off must be made between loads of backpacks and human subjects' safety and comfort. Therefore, it is essential to study backpacks' effect on marchers' efficiency and safety during load carriage.

A few prototypes of biotrack backpacks with a dual-suspension system have been designed and manufactured to investigate the effect of the dual-suspension system on load carriage. However, there is so far no known energy performance analysis of the biotrack suspension systems. Herein, the energy analysis of a new biotrack suspension backpack prototype was first performed. To investigate the improvement of the designed system as background, the index for energy performance analysis of suspension systems was established. Then the adaptation of the method to the detailed numerical analysis and the different energy performance evaluation of the suspension system was illustrated. A thorough analysis of energy performance of the double-suspension system prototype was provided. Several significant characteristics in energy performance of the suspension system for backpacks were unveiled.

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