IDENTIFICATION OF THE RELATIVE MOTION BETWEEN A TORSO AND A BACKPACK WITH DIFFERENT LOADS

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ABSTRACT

This research is part of a larger study at Queen's University to create load-bearing guidelines for the Canadian Forces and to examine the biomechanical effects of carrying heavy loads for long durations. The specific objective is to identify the relative movement between a backpack and a body using a load carriage simulator (LCS) in which a mannequin is driven by computer controlled pneumatic activators to simulate the vertical displacement pattern of walking.

Relative motion and forward lean angle were measured using an accelerometer mounted on the upper chest of the mannequin and an accelerometer mounted inside a backpack placed on the mannequin. The backpack was packed with four different loads – 16.6 kg, 25.9 kg, 38.7 kg and 50 kg. It was found that the mannequin forward lean angle increases with increasing load but there is no distinctive trend in the pack angle. The mean relative differences vary across the four loads, indicating that the relative movement between the torso and pack varies with load. In general, the mean relative differences in the vertical accelerations between the torso and the pack increase with load – however the results for the 25.9 kg load are anomalous. The power spectral densities of the acceleration signals from the four loads also showed distinctive patterns.

I. INTRODUCTION

The use of electronic accelerometers for human physical activity assessment is promising, as they respond to both frequency and intensity of movement. There has been some work done on distinguishing specific tasks from an acceleration profile of body motion. Mäntyjärvi *et al* [1] generated feature vectors as inputs to a neural network classifier by using principle component, independent component and wavelet transform analysis on acceleration data recorded at the hips. Using independent component analysis, they achieved correct classification rates between 83 and 90% for identifying starting and stopping, walking up and down stairs, and level walking.

In 2002, using a record of anteroposterior accelerations, Schultz *et al* [2] were able to estimate the speed of walking and to track the pattern, intensity and duration of daily walking activity from subjects in free living conditions. In a treadmill study involving five different walking speeds, they found that the amplitude of the accelerometer signal was directly related to speed.

Herren *et al* [3] calculated the speed and incline of running using a triaxial accelerometer fixed to the lower back and a uniaxial accelerometer at the heel. They used a neural network classifier to accurately predict running speed with a root mean square error (RMSE) of 0.14 m/s for speeds between 2.6 m/s and 5.8m/s. The incline was not predicted as accurately, where, for slopes ranging from –0.109 rad to +0.109 rad, the RMSE was 0.026 rad.

Morin and Reid [4] conducted a study that measured upper body and pack accelerations from human subjects as they completed a circuit comprised of seven different activities: 1) walking, 2) balance beam, 3) boulder hop, 4) over-under barriers and fence climb, 5) slalom run, 6) up-down ramp and 7) sidehill ramp. Subjects carried a light, medium or heavy load (15.7 kg, 24.455 kg and 34.3 kg) in a backpack.

The upper body accelerations were processed using root mean square (RMS) analysis and spectral analysis. It was found that activities could be ranked based on the magnitude of the RMS value on the three axes ($|RMS| = \sqrt{x^2 + y^2 + z^2}$). The tasks that involved running and those that were performed quickly had the highest |RMS| value. Three activities performed at a slower pace – the over-under, boulder hop and up-down ramp tasks – had a higher |RMS| than walking and the balance beam, slalom run and sidehill ramp tasks had a lower |RMS| than walking. These results suggest a relationship between upper body acceleration and intensity of work performed.

It is likely that task performance is affected by the degree of relative motion between a loaded backpack and the body. The objective of this study is to characterize the relative movement between a backpack and the upper body using the Load Carriage Simulator (LCS) developed at Queen's University.

II. METHOD

The LCS was developed by the Ergonomics Research Group at Queen's University to provide a standardized means of evaluating load carriage systems by assessing certain proven performance parameters. Three main aspects of performance can be analysed: (1) the pressure distribution between the contact surfaces of the backpack and the wearer, (2) the force distribution between the upper torso and the backpack, and, (3) the reaction forces and moments at hip level [5].

The LCS consists of an anthropometrically weighted mannequin (50th percentile male), which is covered with a skin-like surface. It is driven by computer controlled pneumatic activators that are programmed to simulate the vertical displacement pattern of walking by creating a vertical displacement of ±2.54 cm amplitude at 1.8 Hz frequency, where the motion is defined by a sine wave.

The newly designed Clothe the Soldier (CTS) rucksack that has been developed for the Canadian Armed Forces was used in this research. The backpack has been tested using the LCS. In terms of load control, it ranked superior, exhibiting lower average and peak pressures in the anterior and posterior shoulder region, good control of relative pack-torso motion, and lower average reaction moments for vertical, medial/lateral and forward reaction moments at the hip [6].

For this study, the LCS mannequin was outfitted in a military shirt, helmet and the CTS backpack [6]. Two triaxial accelerometers (Crossbow model CXL10LP3) were used. The accelerometers are small (1.9 x 4.76 x 2.54 cm) and light-weight (46-gm). One was mounted on the upper chest of the mannequin, at approximately the position of the sternum. The second was attached to the framesheet of the CTS rucksack. In both cases, the positive y-axis of the accelerometer was oriented vertically upwards. The x-axis orientation was mediolateral (side-to-side) and the z-axis was anteroposterior. The accelerometers were connected to an Embla® data recorder (manufactured by Flaga hf, Reykavik, Iceland), via a hardware interface.

The pack was loaded to a total weight of 16.6, 25.9, 38.7 or 50 kg and placed on the mannequin. The tensions in the shoulder straps and waist belt were adjusted to pre-set values: 1) shoulder strap at 60 N ± 5 N, 2) waist belt at 50 N ± 5 N, 3) upper hip stabilizer strap at 65 N ± 5 N and 4) lower hip stabilizer strap at 65 N ± 5 N [6]. A minimum of ten independent trials were done for each load. Prior to each trial, the backpack was removed and placed back on the mannequin and the shoulder strap and waist belt tensions were re-adjusted to the pre-set values.

At the start of each session (for the four different loads), the mannequin was tilted forward such that the medial-lateral moment measured using a load cell located at the hips was zero.

For each trial the mannequin was set to move at a simulated pace of 1.6 m/s for approximately 15 s. The accelerometer signals were sampled at 100 Hz and stored for off-line processing. A full set of acceleration data (x-, y- and z-axes) was recorded for each of the ten trials at all four loads.

III. RESULTS

A. Mannequin and Pack Tilt Angles

When the mannequin is in the vertical position (the zero load condition), the accelerometer is tilted backwards because of the backward tilt of the upper chest, as shown in Figure 1.

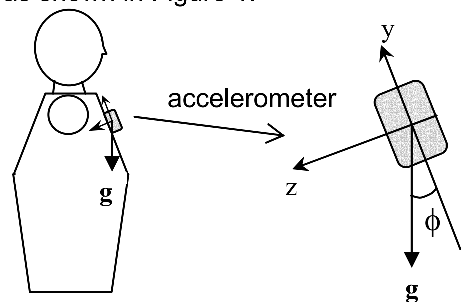

Figure 1: Orientation of accelerometer on the mannequin's upper chest.

Since the accelerometer senses acceleration due to gravity, **g**, it is possible to determine the tilt angle from the projection of **g** on the y (vertical) and z (anteroposterior) axes, where the x (mediolateral) axis has been oriented strictly horizontally. Two six second segments of data were recorded from the accelerometers, with the mannequin in the balanced, stationary position for each load. The tilt angles were calculated using the averaged, stationary data. As well, six seconds of acceleration data from each dynamic trial were used to compute the accelerometer tilt angles. In this case, the mean values on each accelerometer axis were considered to reflect the components of the gravity vector, to a first approximation. The computed angles are given in Table 1 and 2. These results show that the backward tilt of the mannequin accelerometer decreases with load, indicating that the mannequin is rotating forward with load, as expected (i.e. humans tend to lean forward, when carrying a loaded backpack, to orient the centre of mass over the feet).

Table 1: Accelerometer tilt angle for stationary conditions.

Load	Mean Mannequin Angle	Mean Pack Angle
No load	22.56°	No pack
16.6 kg	16.8°	8.26°
25.9 kg	13.21°	1.38°
38.7 kg	9.29°	0.84°
50 kg	0.78°	N/A

Table 2: Accelerometer tilt angle for dynamic conditions.

Load	Mean Mannequin Angle	Mean Pack Angle
16.6 kg	14.40°	1.25°
25.9 kg	12.46°	4.02°
38.7 kg	9.46°	2.01°
50 kg	5.27°	3.74°

B. Relative Motion Between the Mannequin and Pack

In order to compare the mannequin and pack accelerations, the two accelerometers must be aligned. Using the dynamic tilt angles, a rotation matrix was used to align the vertical axes of the accelerometers with the gravity vector. This eliminated the acceleration components on the z-axis and left the accelerations on the vertical axis, which reflect the vertical displacement of the LCS mannequin. The mean absolute relative differences in vertical acceleration between the mannequin and the pack were calculated for the ten trials of the four loads, as shown in Table 3. A plot of the vertical accelerations from a single 16.6 kg trial is shown in Figure 2.

Table 3: Mean of absolute relative differences in vertical accelerations for the different loads.

Load	Mean of absolute relative motion	Standard deviation
16.6 kg	0.37 (m/s^2)	0.02 (m/s^2)
25.9 kg	0.78 (m/s^2)	0.22 (m/s^2)
38.7 kg	0.52 (m/s^2)	0.04 (m/s^2)
50 kg	0.61 (m/s^2)	0.07 (m/s^2)

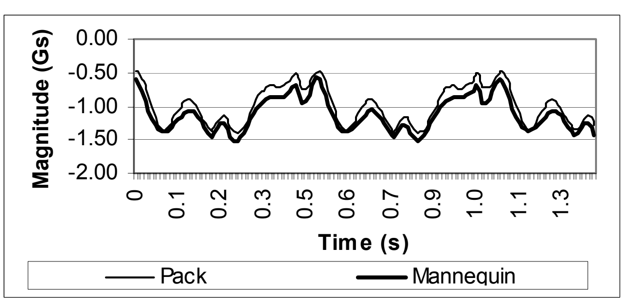

Figure 2: Vertical accelerations of the mannequin's torso and pack for a single 16.6 kg trial.

C. Power Spectral Density of the Vertical Acceleration Signals

The power spectral densities (PSD's) of the vertical accelerations for ten trials of the four loads were calculated and plotted from 0 Hz to 50 Hz. There is a fundamental component at 1.8 Hz, which is the input frequency of the LCS, and several harmonic components. PSD plots for a single trial for each load are shown in Figure 3. Because the power in the 1.8 Hz fundamental frequency is much higher than in the harmonics, the PSD's are plotted from 2.7 – 15 Hz, to highlight the differences between the mannequin and pack accelerations at the harmonic frequencies.

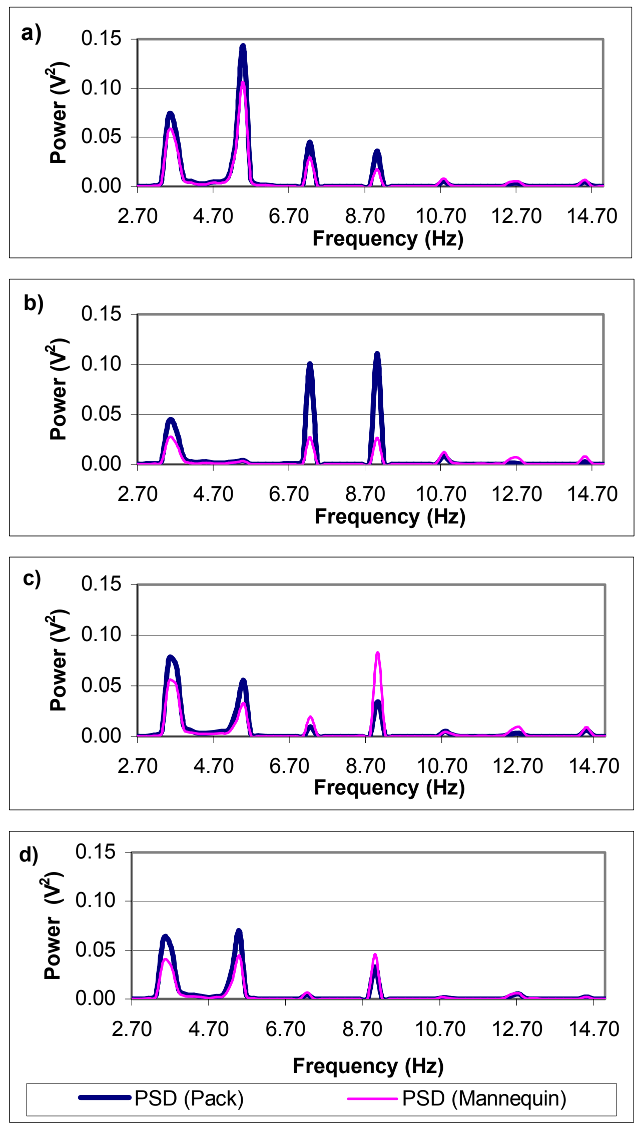

Figure 3: Power spectral density for a) 16.6 kg trial, b) 25.9 kg trial, c) 38.7 kg trial and d) 50 kg trial.

In Tables 4 and 5 the mean total power for frequencies between 0 – 2.7 Hz (the power in the fundamental frequency) and 2.7 – 15 Hz (the power in the 2nd to 8th harmonics) for the mannequin and pack respectively are presented.

Table 4: Mean total power for mannequin.

Load	Mean Total Power (0 Hz – 2.7 Hz)	Standard Deviation	Mean Total Power (2.7 Hz – 15 Hz)	Standard Deviation
16.6 kg	0.60 V^2	0.04 V^2	0.31 V^2	0.03 V^2
25.9 kg	0.63 V^2	0.01 V^2	0.16 V^2	0.01 V^2
38.7 kg	0.64 V^2	0.05 V^2	0.32 V^2	0.01 V^2
50 kg	0.66 V^2	0.03 V^2	0.26 V^2	0.02 V^2

Table 5: Mean total power for pack.

Load	Mean Total Power (0 Hz – 2.7 Hz)	Standard Deviation	Mean Total Power (2.7 Hz – 15 Hz)	Standard Deviation
16.6 kg	0.76 V^2	0.05 V^2	0.40 V^2	0.04 V^2
25.9 kg	0.74 V^2	0.01 V^2	0.31 V^2	0.05 V^2
38.7 kg	0.82 V^2	0.05 V^2	0.34 V^2	0.01 V^2
50 kg	0.88 V^2	0.02 V^2	0.33 V^2	0.02 V^2

IV. DISCUSSION

In this study, acceleration signals from the mannequin of the LCS and a loaded backpack were recorded to examine the relative position and the relative movement between the body and the pack for different pack loads. As expected, there was an increase in forward lean angle of the mannequin with increasing load. There is no distinctive trend in the pack angle and the pack angle did not follow the mannequin angle. This may be due to rotation of the pack on the body, caused by the load, where the amount of rotation may be a function of the characteristics of the pack suspension system.

The mean relative differences in the vertical accelerations between the torso and the pack appear to increase with load, if the value for the 25.9 kg load is disregarded. The 25 kg load trials were conducted before the other trials and the protocol may have varied; this may have contributed to the anomalous mean relative difference and the much higher standard deviation. The mean relative differences did vary for all four loads, indicating that the relative movement between the torso and pack varies with load.

There were distinctive patterns in the PSD's for all four loads. The total power increased as load increased for frequencies between 0 Hz and 2.7 Hz. For the 16.6 kg load, the highest power was in the 3rd harmonic frequency (5.4 Hz). For the 25.9 kg load, the highest power harmonics were the 4th and 5th (7.2 and 9.0 Hz). For the 38.7 kg load and the 50 kg load, the highest power was in the 2nd, 3rd and 5th harmonics (3.6, 5.4 and 9 Hz); the PSD's of these two loads are distinguishable, however, because of the difference in spectral power at 3.6 and 9 Hz.

Given the distinctive patterns in the PSD's of the mannequin and pack accelerations, future work will involve using this information as input to a neural network to predict the pack's motion from the motion of the mannequin for a given load and a given backpack.

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