DRDC TORONTO CR 2009-197

DEVELOPMENT OF A PORTABLE DATA ACQUISITION SYSTEM FOR HUMAN PERFORMANCE ASSESSMENT IN THE FIELD - PHASE IIB

VALIDATION

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PWGSC Contract No. 7711-0-7632/01-TOR
Call up #7632-04

On behalf of

DEPARTMENT OF NATIONAL DEFENCE

as represented by

Defence Research and Development Canada - Toronto

1133 Sheppard Avenue West

North York, Ontario, Canada

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416-635-2000 X3215

December 2007

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Abstract

A second module, Module 2 – the Activity Assessment Module (AAM) – has been developed for the portable data acquisition system for human performance evaluation. The main purpose of the AAM is to permit the assessment of the type and intensity of work performed by a subject in the field, e.g. a soldier participating in a training exercise. This is done using two primary measures: upper body accelerations on three axes and heart rate (HR).

The AAM was evaluated in an in-door trial. Upper body accelerations and HR were monitored in subjects as they completed a standardized circuit. The subjects carried either a very light load (battle order conditions); or a light, medium or heavy load (marching order conditions). The circuit comprised seven discrete activities: walking, balance beam, boulder hop, over-under barriers and fence climb, slalom run, up-down ramp, and sidehill ramp. The results of the trial revealed the following:

- metabolic energy cost, estimated from HR, increases with increasing load carried
- metabolic energy cost, estimated from HR does not vary with the activity performed
- specific tasks can be recognized from recorded upper body accelerations
- tasks can be ordered by the magnitude of the root mean square (RMS) value of the acceleration signal, suggesting that there is a relationship between the acceleration of the body and the intensity of the work performed

The AAM performed well in comprehensive testing and promises to be a valuable tool for monitoring soldier activity.

Résumé

Un deuxième module, le Module 2 – le module d'évaluation de l'activité (MEA) – a été élaboré pour le système portatif d'acquisition de données destiné à évaluer la performance humaine. L'objectif principal du MEA est d'évaluer le type et l'intensité des travaux réalisés par une personne sur le terrain, p. ex. un soldat qui participe à un exercice d'entraînement. Deux types de mesures permettent cette évaluation : ce sont la mesure de l'accélération de la partie supérieure du corps sur trois axes, et la mesure du rythme cardiaque (RC).

Le MEA a été évalué lors d'un essai à l'intérieur. L'accélération de la partie supérieure du corps et le RC ont été surveillés chez les participants qui faisaient un circuit normalisé. Les participants transportaient soit une charge très légère (attirail de guerre), ou une charge légère, moyennement lourde ou lourde (attirail de route). Le circuit comprenait sept activités distinctes : marcher, passer sur une poutre d'équilibre, ramasser un bloc, passer au-dessus et en dessous d'une clôture et la grimper, courir en slalom, monter-descendre une rampe, et enfin passer sur une rampe ayant la forme d'une colline. Les résultats de l'essai ont permis de déterminer que :

- la dépense énergétique liée au métabolisme, estimée à partir du RC, augmente en fonction de la charge transportée;
- la dépense énergétique liée au métabolisme, estimée à partir du RC, ne varie pas selon l'activité réalisée;
- chaque tâche spécifique peut être identifiée d'après l'accélération enregistrée pour la partie supérieure du corps;
- les tâches peuvent être classées en fonction de la valeur de la moyenne quadratique (MQ) du signal d'accélération, ce qui laisse supposer qu'il existe un lien entre l'accélération du corps et l'intensité du travail effectué.

Le MEA a donné des résultats intéressants lors de l'essai global et devrait être un outil valable pour l'évaluation éventuelle de l'activité des soldats.

Executive Summary

A second module, Module 2 – the Activity Assessment Module (AAM) – of the portable data acquisition system for human performance evaluation was tested in a comprehensive human trial. Using the AAM, upper body acceleration was measured on three axes – mediolateral (*x*-axis), vertical (*y*-axis) and anteroposterior (*z*-axis). Subjects completed a standardized indoor activity circuit, under one of two regimens: battle order (BO) testing and marching order (MO) testing. In BO testing, subjects carried a load of approximately 10 kg and completed the activity circuit at a running pace. In MO testing, subjects carried each of three different loads (15.7 kg, 24.455 kg and 34.3 kg) in a backpack and completed the circuit at a walking pace. The activity circuit comprised seven tasks grouped into walking or running and four activity stations: balance beam and boulder hop; over-under and fence climb; slalom run and up-down ramp; and sidehill ramp. Heart rate (HR) was monitored throughout the trial.

The subjects' energy expenditure (EE) was estimated from HR and found to increase with increasing load, but did not vary significantly with activity station. The power in the acceleration signals, summed over all subjects and all activities also increased with increasing load. However, this effect was not noted for average power for each activity separately.

The recorded acceleration signals were processed using root mean square (RMS) analysis and spectral analysis. It was found that activities could be ranked by the magnitude of the RMS values on the three axes ($|RMS| = \sqrt{x^2 + y^2 + z^2}$). Running and tasks performed quickly had the highest $|\mathrm{RMS}|$; for activities performed at a slower pace, the over-under, boulder hop and up-down ramp tasks had a higher $|\mathrm{RMS}|$ than walking and the balance beam, slalom run and side hill ramp tasks had a lower $|\mathrm{RMS}|$ than walking. The power spectra of the acceleration signals were computed and showed distinctive differences with activity. The acceleration data were analyzed using Matlab®, Excel® and software specifically developed for this application (CoAn™).

The results of the human trial indicate that information regarding the type and intensity of activity performed can be determined from measured upper body accelerations. Upper body accelerations can be supplemented with HR information to estimate EE. Future work will include a validation of the correlation between acceleration, HR and EE under load and extend the data processing capabilities of the CoAn™ software developed under this contract.

Sommaire

Un deuxième module, le Module 2 – Module d'évaluation de l'activité (MEA) – du système portatif d'acquisition de données pour l'évaluation de la performance humaine a été testé lors d'un essai global. À l'aide du MEA, l'accélération de la partie supérieure du corps a été mesurée sur trois axes, soit l'axe médio-latéral (axe des *x*), l'axe vertical (axe des *y*) et l'axe antéro-postérieur (axe des *z*). Les participants ont fait deux circuits d'activité normalisés différents, à l'intérieur, l'un avec un attirail de guerre (AG) et l'autre avec un attirail de route (AR). Lors de l'essai avec l'AG, les participants transportaient une charge d'environ 10 kg et faisaient le circuit au pas de course. Lors de l'essai avec l'AR, les participants transportaient chacun des charges différentes (15,7 kg, 24,455 kg et 34,3 kg) dans un sac à dos pour un circuit effectué en marchant. Le circuit comportait sept tâches effectuées en marchant ou en courant et quatre stations (activités) : passer sur une poutre d'équilibre et ramasser un bloc; passer au-dessus et en dessous d'une clôture, et la grimper; courir en slalom et monter-descendre une rampe; et passer sur une rampe ayant la forme d'une petite colline. Le rythme cardiaque (RC) a été surveillé pendant toute la durée de l'essai.

La dépense énergétique (DE) des participants a été estimée à partir du RC et était proportionnelle à la charge, mais ne variait pas de manière importante en fonction de la station (activité). La puissance des signaux d'accélération, dont la somme a été calculée pour tous les participants et toutes les activités, augmentait également en fonction de l'accroissement de la charge. Cependant, cet effet n'a pas été noté en ce qui a trait à la puissance moyenne pour chaque activité séparément.

Les signaux d'accélération enregistrés ont été traités dans le cadre d'une analyse de la moyenne quadratique (MQ) et d'une analyse spectrale. Il a été déterminé que les activités pouvaient être classées selon la valeur de la MQ sur les trois axes ($|MQ| = \sqrt{x^2 + y^2 + z^2}$). La course et les tâches effectuées rapidement avaient la |MQ| la plus élevée; dans le cas des activités réalisées à un rythme plus lent, soit passer au-dessus et en dessous d'une clôture, ramasser un bloc et monter-descendre une rampe, la |MQ| était plus élevée que pour la marche; et les activités qui consistaient à marcher sur une poutre d'équilibre, à courir en slalom et à passer sur la rampe en forme de colline avaient une |MQ| plus faible que la marche. Le spectre de puissance des signaux d'accélération a été calculé, et faisait état de différences notables pour les

diverses activités. Les données relatives à l'accélération ont été analysées à l'aide de Matlab®, d'Excel® et d'un logiciel conçu expressément pour cette application (CoAn™).

Les résultats des essais indiquent que l'information sur le type et l'intensité de l'activité réalisée peut être déterminée d'après les accélérations mesurées pour la partie supérieure du corps. Les accélérations de la partie supérieure du corps peuvent être complétées par l'information sur le RC dans le but d'estimer la DE. Les travaux à venir consisteront notamment à valider la corrélation entre les accélérations, le RC et la DE sous l'effet d'une charge, et à accroître la capacité de traitement des données du logiciel CoAn™ mis au point dans le cadre du présent contrat.

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1. Introduction

Development of a portable system for monitoring soldier performance during training and field exercises was begun under contract #W7711-997598/001/TOR for Defence Research and Development Canada (DRDC) – Toronto (formerly the Defence and Civil Institute of Environmental Medicine – DCIEM). The system is designed to be modular, allowing for independent sets of relevant physiological and biomechanical variables to be measured. The first proposed module (Module 1) would permit measurement of parameters applicable to gait analysis, i.e. hip, knee and ankle joint angles and ground reaction forces. Development of this module is continuing under a separate contract.[1]

A second module, Module 2 – the Activity Assessment Module – which provides measures of both physiological parameters (heart rate and skin surface temperature) and biomechanical parameters (body acceleration and backpack strap tensions) has been developed. The implementation of this module is described in a separate report (Morin and Reid, 2002). Sixteen channels of data are sampled and stored using the Embla®[2] data recorder. The data channels include six accelerometer channels (supporting two triaxial accelerometers), two surface temperature channels, two ECG channels and six strap tension transducer channels.

The ultimate goal of the portable system development is to integrate physiological and biomechanical measures to obtain a complete picture of the operational effectiveness of a soldier in the field. Performance information to be obtained from Module 2 includes an estimate of the energy cost of activity, and a quantitative measure of soldier mobility and agility, via the identification of specific tasks performed during field trials.

1.1. Estimating Metabolic Energy Cost

Metabolic energy cost is an important measure for determining the efficiency with which an individual performs a task, and the potential duration over which the individual could be expected to work. The two primary means by which energy cost is estimated are indirect calorimetry and non-calorimetric methods (Murgatroyd et al., 1993). Indirect calorimetry involves measuring O_2 consumption and CO_2 production by collecting a subject's expired air

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[1] DRDC Contract no. 7711-0-7632/01-TOR; Call-up no. 7632-05

[2] Manufactured by Flaga^{hf}, Reykavik, Iceland: www.flaga.is

over a period of time. Expired air is collected using a face mask or mouthpiece or is drawn from an enclosure surrounding the subject. Portable instrumentation to measure gas exchange is available (e.g. the VO2000 from MedGraphics Corp., St. Paul, MN[3]) however, such instrumentation involves the use of a mask or mouthpiece, which is not acceptable for use by soldiers in the field.

Non-calorimetric methods of assessing energy cost do not involve the analysis of expired air, and thus do not require a face mask or mouthpiece. In the doubly labelled water technique, subjects ingest a single dose of $^2H_2{}^{18}O$ and the turnover of the two isotopes, ^2H and ^{18}O, is monitored over an adequate period of time (1-2 weeks). CO_2 production rate and total metabolic energy cost is determined from the difference in the disappearance rates of the two isotopes. This method provides only an average total energy cost – energy expenditure (EE) cannot be tracked over time. The method is also expensive and time-consuming (Murgatroyd et al., 1993).

Heart rate (HR) has been shown to be directly correlated to O_2 uptake during physical activity. A measure of HR over time can be easily obtained with commercially available systems. However, an HR-O_2 calibration curve must be defined for each individual during steady-state, constant-load exercises and it is not possible to obtain an accurate resting EE estimate from HR. As well, HR is influenced by factors such as fitness level, ambient humidity, ambient temperature, emotional state, posture, substances such as nicotine and caffeine, and digestion. These affect the accuracy of the EE estimate. (Li et al., 1993; Murgatroyd et al., 1993)

More recently, the relationship between human movement and O_2 consumption has been explored. Reswick et al. (as noted in Wong et al., 1981) reported that the integral of absolute vertical acceleration, as measured by an accelerometer mounted on the head, was correlated with O_2 consumption during walking. Given this evidence, Wong et al. (1981) developed a portable device to measure EE per unit time by sensing the vertical acceleration of the human body during locomotion. They evaluated their device against a measure of O_2 consumption for walking at various speeds and for bench-stepping exercises. They found that the output of their device was correlated with measured O_2 consumption and reported a correlation of 0.74 for activities performed in a laboratory setting (Montoye et al., 1983). This was the basis for

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[3] www.medgraphics.com

development of the Caltrac[4] monitor, which is still widely used. Another activity monitor, which measures vertical accelerations, was developed by Computer Science and Applications, Inc. – the CSA monitor[5]. The use of the CSA monitor to estimate EE was validated in a treadmill test against EE measured using indirect calorimetry; the CSA monitor was also compared to the Caltrac (Melanson and Freedson, 1995). The performance of the CSA and Caltrac monitors was found to be comparable. Both monitors were sensitive to changes in treadmill speed, but not treadmill grade. Both monitors could accurately predict mean EE but neither accurately predicted EE in individuals. It was found that the accuracy of the estimated EE was improved when readings from two or three CSA monitors, mounted on the limbs and trunk, were used to predict EE.

A triaxial accelerometer system, the Tritrac-R3D[6] was developed to overcome the limitations of the uniaxial accelerometer for estimating EE (Chen and Sun, 1997). The Tritrac is worn at the hip and monitors accelerations on the x (anteroposterior), y (medial-lateral) and z (vertical) axes. The vector magnitude, $\sqrt{x^2 + y^2 + z^2}$ is used to estimate the EE. Chen and Sun (1997) validated the Tritrac against a whole room indirect calorimeter over two days and found that the Tritrac underestimated the total EE, as well as EE for specific activities. They developed two models, a linear and non-linear model, based on separation of the vertical (z) and horizontal (x and y) acceleration components. Using their models, they were able to estimate EE with higher accuracy.

Bouten et al. (1994) also studied the use of a triaxial accelerometer for measuring EE. The aim of their study was to evaluate the relationship between whole body acceleration and EE due to physical activity, including both sedentary activities and walking at different speeds. The accelerometer data were processed to obtain the integrated absolute value on each axis (x – anteroposterior; y – medial-lateral; z – vertical); a total integrated absolute value (summed over the three axes); an estimate of the kinetic energy, where the kinetic energy of a

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[4] For example, see http://www.muscledynamics.net/caltrac/

[5] The CSA monitor is now marketed as the Actigraph activity monitor (http://mtiactigraph.com/) by Manufacturing Technology Incorporated, Fort Walton Beach FL.

[6] The Tritrac monitor, manufactured by Hemokinetics Inc., Madison, WI has been used in several research studies. However, no information on the device is currently available on the World Wide Web. A comparable device, the RT3 monitor is available from Stayhealthy Inc., Monrovia, CA (www.stayhealthy.com) .

moving body is ½($m_b v^2$), m_b is the body mass and v is the velocity; and the rate of change of kinetic energy. During walking, the most accurate predictor of energy cost was the integrated absolute value of anteroposterior acceleration (IAA_x), followed by the sum of the integrated absolute accelerations (IAA_{tot}). Based on these two parameters, Bouten et al. identified two regression equations using pooled data from all subjects, which can be used to estimate the energy cost of an activity. Using the second equation, $EE_{act} = 0.104 + 0.023 IAA_{tot}$, the EE for walking and sedentary activities could be estimated to within 15% accuracy. As with the uniaxial accelerometer, however, the energy cost of sedentary activities is underestimated.

Bouten et al. extended the above work to the development of a portable monitor, based on use of a triaxial accelerometer, for assessing daily physical activity (Bouten et al., 1997). EE was estimated by computing the sum of the integrated absolute values of the accelerations on the three axes (a_1, a_2 and a_3) over the desired time period, T:

$$IMA_{tot} = \int_{t_0}^{t_0+T} |a_1|\,dt + \int_{t_0}^{t_0+T} |a_2|\,dt + \int_{t_0}^{t_0+T} |a_3|\,dt$$

The accuracy of the monitor was tested using 13 subjects who performed a standardized activity protocol. The energy expenditure estimated by the monitor was compared to EE measured using indirect calorimetry. The protocol included sedentary activities – e.g.: sitting, lying and desk work – and more intensive activities – e.g.: walking, bench stepping and load carrying. IMA_{tot} tracked the energy cost of the prescribed activities, but it was found that, for intensive activities, EE was underestimated by an average of 6.2%, and for sedentary activities, EE was overestimated by an average of 6.6%.

Luke et al. (1997) combined measured HR and body motion to assess whether a more accurate prediction of EE could be obtained. Motion was measured using tilt sensors mounted at the waist; HR was monitored independently. Subjects participated in two tests – performance of an activities of daily living circuit and a submaximal treadmill test. O_2 consumption was measured concurrently and compared to $\dot{V}O_2$ estimated from motion data, HR data and combined motion and HR data. It was found that motion alone is a poor predictor of O_2 consumption; HR alone is a good predictor of O_2 consumption, except for low intensity activities. Using HR plus motion, a better estimate of O_2 consumption during low intensity activities is obtained. Individual HR-O_2 calibration curves are still required when HR and motion are combined to estimate energy cost.

Recently, the ability of accelerometer-based physical acitivty monitors to accurately estimate moderate level physical activity under field conditions has been studied. Hendelman et al. (2000) evaluated the CSA and Tritrac monitors against indirect calorimetry for overground walking, golfing and typical indoor and outdoor household tasks (e.g. cleaning windows, lawn mowing). The values reported by the monitors were reasonably well correlated with measured EE for walking, but the monitors underestimated the EE of golfing and household activities by 30%-60%. Welk et al. (2000) compared the CSA monitor, Tritrac and Biotrainer[7] for assessing physical activity under lab conditions and under field conditions and evaluated the monitors against EE measured using indirect calorimetry. EE was measured for walking, brisk walking and jogging on a treadmill (lab activities) and for either mowing, raking and shoveling or vacuuming, sweeping and stacking groceries (field activities). Strong correlations were found between the outputs of all activity monitors and EE measured using indirect calorimetry for the lab activities. Correlations were much weaker for the field activities. For the lab activities, the EE estimates from the CSA monitor were within 3.3% of the measured EE; the Tritrac and Biotrainer monitors overestimated EE by 112%-128%. For the field activities, the magnitude of the estimation error was 38%-48% for all three monitors. The EE was underestimated in all cases. Campbell et al. (2002) compared the Tritrac monitor against indirect calorimetry to evaluate EE for a series of activities performed by female subjects. It was found that the Tritrac overestimated EE for walking, jogging and walking on an incline and underestimated EE for stair climbing, stationary cycling and arm ergometry. For the last two activities, which are non-wieght bearing, Tritrac greatly underestimated the energy cost. Using Chen and Sun’s (1997) non-linear model on the raw Tritrac data, Campbell et al. obtained a significant improvement in the estimates for walking, jogging and walking on an incline.

The results of the above studies indicate that activities such as isometric contractions, upper body movement, load bearing, and changes in terrain during walking are not well detected by accelerometers worn at the waist (Hendelman et al., 2000). It has been noted that, in general, accelerometer-based activity monitors overestimate EE for activities with a small force:displacement ratio (e.g. jumping and running) and underestimate EE for activities with a

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[7] See http://www.imsystems.net/BioTrainer2-.html (IM Systems, Baltimore, MD). The BioTrainer is a single-axis accelerometer unit.

large force:displacement ratio (e.g. stair climbing) (Welk et al., 2000; Campbell et al., 2002). In order to provide an accurate estimate of energy cost, over short terms or long durations, these issues need to be addressed.

1.2. Detecting Human Movement Patterns

Some effort has been made to differentiate specific tasks from an acceleration profile of body motion. Using two triaxial accelerometers worn at the hip, Mäntyjärvi et al., (2001) used principle component and independent component analysis combined with a wavelet transform to generate feature vectors for input to a neural network classifier. They obtained their best results using independent component analysis, achieving correct classification rates of 83-90% for starting/stopping, level walking, walking up stairs and walking down stairs. In terms of incorrect classifications, it was most likely that walking up stairs and walking down stairs would be misclassified as level walking. Schutz et al. (2002) were able to track the pattern, intensity and duration of daily walking activity, as well as estimate the speed of walking, in subjects in free living conditions from a record of anteroposterior accelerations. In a treadmill study, involving 5 walking speeds, they found that the amplitude of the accelerometer signal is directly related to speed. Thus, the average walking speed, over level terrain could be reasonably estimated for subjects walking freely. However, since the energy cost of walking is influenced by incline, as well as speed, Schutz et al. did not attempt to estimate energy cost. Herren et al. (1999) were able to calculate the speed and incline of running using a triaxial accelerometer fixed to the lower back and a uniaxial accelerometer at the heel. They also found that the amplitude of the acceleration signals increased with speed; the parameter of the acceleration signals that was most highly correlated with incline was the median value of the vertical acceleration. The shift in this value reflects the increased vertical accelerations needed to move up an incline. Using a neural network classifier, running speed was accurately predicted, with a root mean square error (RSME) of 0.14 m/s for running speeds between 2.6 and 5.8 m/s; incline was less accurately predicted, with an RSME of .026 rad for slopes ranging from –0.109 rad to +0.109 rad.

The results of the above studies indicate that certain characteristics of specific activities are reflected in the whole body accelerations, which would permit these activities to be identified from an acceleration record.

2. Objectives

The objectives of the work done for this contract report are:

- To test the operation of the instrumentation developed for portable system module 2
- To measure whole body acceleration patterns for a series of well defined activities
- To evaluate the use of measured whole body acceleration to determine:
    - an individual's activity pattern, including a measure of the intensity of the activities performed
    - the effect of equipment on task performance; specifically the effect of load carried in a backpack

3. System Testing and Data Collection

3.1. Hardware Testing

Testing of the sensors and the hardware interface are described in the previous contract report (Morin and Reid, 2002). The sensors were connected via the hardware interface to the Embla recorder and the recorder was configured to run in ambulatory mode. Data were stored by the recorder on a resident SDCFBS-64-101-50 SanDisk[8] CompactFlash™ (storage capacity 64Mb).

3.2. Human Trials using a Standardized Mobility Circuit

Once proper operation of the instrumentation was confirmed, a comprehensive indoor mobility and agility test, to collect data specific to the performance of human subjects, was run in December 2001. Thirteen male subjects participated in the study. The average age, height and mass of the subjects was: 21.8±2.6 years, 177.8±4.2 cm and 76.4±6.4 kg respectively. Each subject signed an informed consent form, which is included in Appendix A. Prior to testing, each subject's fitness level was assessed and maximum $\dot{V}O_2$ was estimated, using a beep test, which is described in Appendix B.

The testing consisted of two regimens: battle order (BO) testing and marching order (MO) testing. In BO testing, a triaxial accelerometer (Crossbow model CXL10LP3) was

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[8] SanDisk Corporation, Sunnyvale CA, www.sandisk.com

affixed at approximately the middle of the sternum. The accelerometer was mounted such that the *x*-axis was oriented left-right (positive to the right) to detect mediolateral motion; the *y*-axis was oriented up-down (positive upwards) to detect vertical motion and the *z*-axis was oriented in the forwards-backwards direction (positive backwards) to detect anteroposterior motion. The accelerometer was connected to the Embla data recorder, via the hardware interface. The data collection instrumentation was carried in a daypack comprising a total weight of approximately 4 kg. Subjects were equipped with a military issue tactical assault vest (TAV), which weighed 4.5 kg, a helmet, and a model rifle identical in weight and size to rifles used by the Canadian Armed Forces. The purpose of the BO testing was to assess the robustness and integrity of the data collection instrumentation and to record an initial set of upper body accelerations for a set of defined tasks.

In MO testing, subjects were asked to carry one of two large backpacks, containing either a 15.7 kg (L) load; 24.455 kg (M) load or a 34.3 kg (H) load. An accelerometer was affixed to the sternum, in the same orientation as in the BO tests. A second accelerometer was fixed inside the backpack to the centre of the framesheet[9]. The data collection instrumentation was carried in the backpack. MO testing was carried out over two sessions, with a minimum of 45 hours rest between trials. On day 1, subjects carried all three loads, in random order, in one of the two packs – designated CTS and DFS; on day 2 subjects carried all three loads, in random order, in the second pack. The CTS pack is the accepted design for the next genreation Canadian Armed Forces backpack; the DFS (dynamic frame sheet) pack is an original design which permits limited motion between the load volume and the pack suspension system in order to reduce the energy demand on the wearer. In the MO testing, accelerations were recorded from the upper body and from the backpack for the same set of defined tasks as in the BO testing, under the three load conditions.

In each test regimen, subjects were asked to complete the standardized test circuit shown in Figure 1. At the beginning of each test, the subject ran (BO testing) or walked (MO

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[9] This accelerometer was positioned such that the *x*-axis was oriented in the left-right direction, positive *x* to the left; the *y*-axis was oriented vertically, positive upwards; and the *z*-axis was oriented in the anteroposterior direction, positive anterior. Accelerations measured by this accelerometer are being analysed to determine the relative motion of the backpack with respect to the bearer and will be used as input to a Dynamic Biomechanical Model of load carriage. This work is being done under DRDC-Toronto, contract # 7711-0-7632/01-TOR; call up #7632-06.

testing) twice around the perimeter of the circuit. At the end of each lap, the subject passed the Start position; at the end of the second lap, the subject was required to pass the Start position and then proceed to station 1 – balance beam and boulder hop. The subject was instructed to perform the task twice and then proceed to the Start position and run or walk twice around the perimeter. This was repeated for station 2 – over-under and fence climb (down and back), station 3 –slalom run and up-down ramp, and station 4 – sidehill ramp (down and back). At the end of the final station, the subject again walked or ran twice around the perimeter. In the BO testing, a 20-m leopard crawl was added to the end of the circuit. In addition to the acceleration data, the subject's heart rate and the elapsed time were recorded each time the subject passed the Start position.

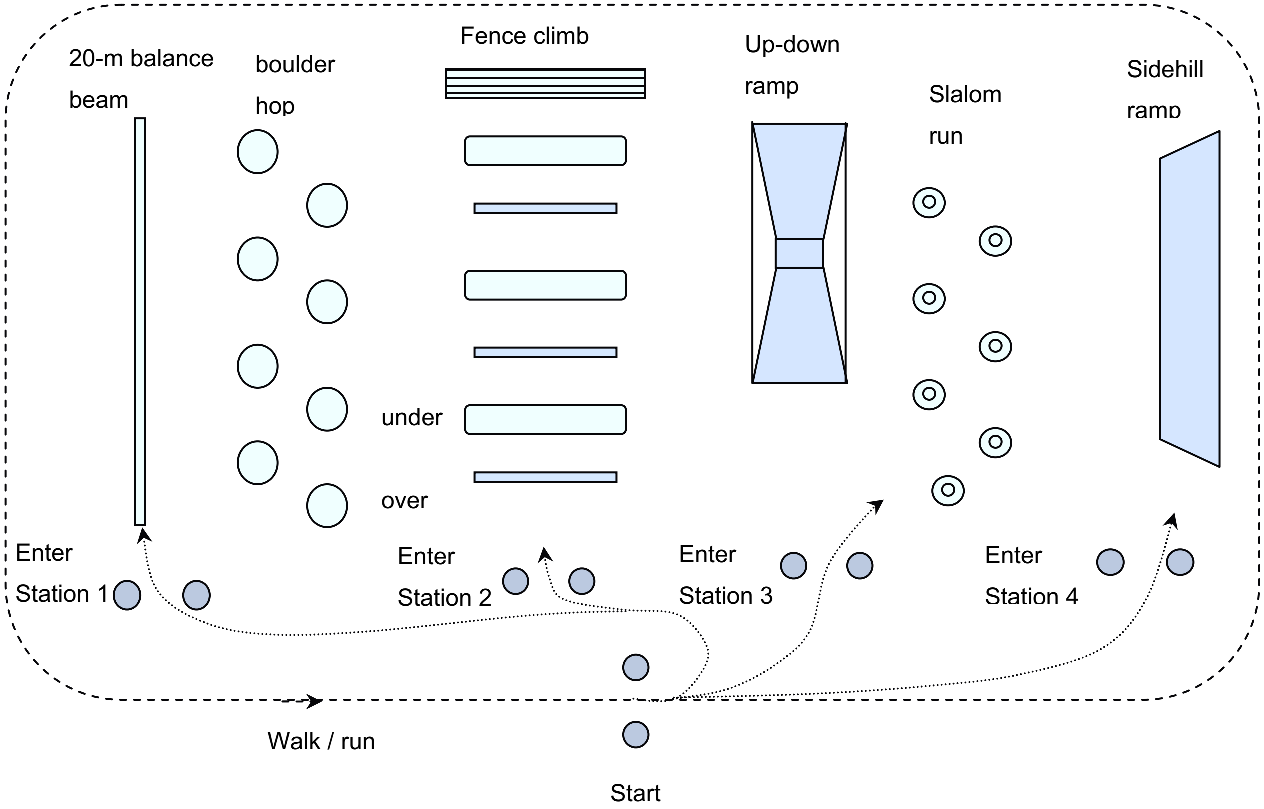


Figure 1: Standardized activity circuit

4. Results and Data Analysis

4.1. Acceleration Signals

Full sets of acceleration data were obtained from three BO trials and from seven MO trials. For each BO subject, a set of *x*-, *y*- and *z*-axis accelerations were recorded for one completion of the test circuit; for each MO subject, a set of *x*-, *y*- and *z*-axis accelerations were recorded for three completions of the circuit – one for each of the three load conditions. Subject and trial numbers, for which full data sets were recorded, the load conditions for the MO trials, and the time taken to complete the circuit for each subject are given in Table I.

Table 1: Summary of Human Trial Conditions

BO Trials		**MO Trials**						
Subject #	Circuit time	Subject # and load condition	Circuit 1		Circuit 2		Circuit 3	
			Load	Time	Load	Time	Load	Time
1BO	5m 13s	7MOA-CTS	M	12m 45s	H	11m 16s	L	10m 09s
2BO	6m 33s	7MOB-DFS	H	12m 05s	L	10m 10s	M	11m 25s
6BO	4m 14s	8MOA-CTS	M	13m 59s	H	13m 46s	L	13m 35s
		8MOB-DFS	M	13m 40s	L	14m 30s	H	13m 30s
		11MOB-CTS	H	14m 22s	M	13m 24s	L	12m 55s
		12MOA-DFS	M	11m 02s	L	13m 06s	H	12m 36s
		13MOA-DFS	H	12m 27s	M	12m 38s	L	11m 18s

As described in the previous report, the output voltages of the Crossbow accelerometers are attenuated to lie between 0 and 250 mV before they are sampled and stored by the Embla recorder. Because of the connector polarity, the stored data are negative (i.e. they lie between 0 and –250 mV). The Embla recorder stores the data in a specific file format, which can only be opened by the dedicated software package provided with the Embla system (Somnologica v.3, ©Flaga hf. Medical Devices). The acceleration data were examined visually in Somnologica to identify the start and end times of the tasks performed. This was done given that the order in which the tasks were performed was known, the acceleration records for certain tasks exhibited characteristic patterns (as discussed below) and the transitions between the tasks could be identified. The task profile for the test circuit is given in Table 2; the activity stations have been identified in the Table. From Somnologica, the data were copied into text files for further processing using Excel, Matlab and dedicated analysis software developed specifically for this project. Root Mean Square (RMS) and power spectral analysis of the data has been done by task and is reported in Sections 4.2 and 4.4; metabolic energy cost analysis has been done by activity station and is reported in Section 4.3.

Table 2: Task profile for subject activity circuit

Activity	**Activity Station**
Run (BO) or Walk (MO) 1 (2 laps)	*Lap 1 and 2*
Balance beam 1	Station 1 – 1st repetition
Boulder hop 1	
Balance beam 2	Station 1 – 2nd repetition
Boulder hop 2	
Run (BO) or Walk (MO) 2 (2 laps)	*Lap 3 and 4*
Over-Under barriers 1 (with fence climb – over and back)	Station 2 – 1st repetition
Over-Under barriers 2	
Over-Under barriers 3 (with fence climb – over and back)	Station 2 – 2nd repetition
Over-Under barriers 4	
Run (BO) or Walk (MO) 1 (2 laps)	*Lap 5 and 6*
Slalom run 1	Station 3 – 1st repetition
Up-down ramp 1	
Slalom run 2	Station 3 – 2nd repetition
Up-down ramp 2	
Run (BO) or Walk (MO) 1 (2 laps)	*Lap 7 and 8*
Sidehill ramp 1	Station 4 – 1st repetition
Sidehill ramp 2	
Sidehill ramp 3 and return to start	Station 4 – 2nd repetition
Run (BO) or Walk (MO) 1 (2 laps)	*Lap 9 and 10*

The sampled data values are converted to acceleration values in g's of acceleration using:

$$\text{accel} = \left(\frac{-1 \times \text{data value}}{\text{scale factor}} - \text{zero g voltage} \right) \times \frac{1}{\textit{sensitivity}}$$

where scale factor is 0.0447; zero g voltage is 2.49V on the *x*-axis, 2.486V on the *y*-axis and 2.484V on the *z*-axis; and sensitivity is 0.197 V/g on the *x*-axis, 0.202 V/g on the *y*-axis and 0.202 V/g on the *z*-axis.

Representative acceleration curves, from a single MO subject, for each of the seven tasks (walking, balance beam, boulder hop, over-under barriers, slalom run, up-down ramp and sidehill ramp) performed in the activity circuit are shown in Figure 2. The walking pattern exhibits a relatively large, periodic acceleration in the vertical (*y*-axis) direction. This reflects the vertical lift of the body as each foot is lifted off the ground and the leg swings through to the next stance phase of the gait cycle. The period of the acceleration waveform is approximately 0.46s, giving a step frequency of 2.17 Hz. This is consistent with a typical gait frequency of 2 Hz (Inman et al. 1981). There is also a regular pattern in the left-right acceleration (*x*-axis), which is at half the frequency of the vertical acceleration. This is due to the side-to-side motion as the body is centred over the planted foot during the gait cycle. The downward spike on the anteroposterior (*z*-) axis acceleration record indicates a rapid forwards acceleration during each phase of the gait cycle followed by a slowing of forward motion (acceleration in the +*z* or posterior direction). The pattern of acceleration during walking is consistent across the MO subjects. The same general pattern of acceleration is apparent during running in the BO subjects, except that the acceleration amplitudes are greater than for walking and the acceleration record indicates a gait frequency of approximately 3 Hz.

Patterns similar to the walking pattern are evident in the accelerations recorded during the balance beam, slalom run, up-down ramp and sidehill ramp tasks. These tasks all involve upright mobility, but the balance beam, slalom run and sidehill ramp tasks also require agility and the maintenance of balance during performance of the task. In the agility tasks, the amplitude of the vertical accelerations is reduced, and particularly in the slalom run, the pattern is less regular. The change in the *x*-axis pattern, in the balance beam and slalom run records, indicates side-to-side tilt as the subject performs the task. The up-down ramp record exhibits a typical pattern of increasing vertical acceleration as the subject ascends the ramp and decreasing acceleration as the subject descends. The *x*-axis record has changed somewhat, particularly on the downward side of the ramp, indicating a change in gait pattern in order to maintain balance during descent.

The acceleration patterns recorded during the boulder hop and over-under barrier tasks differ considerably from the walking pattern. This is to be expected as these tasks involve a primary motion other than upright mobility. In the boulder hop task, the subject leapt in a zig-zag pattern between markers placed on the floor. In the *x*-axis acceleration record, there is a distinctive pattern indicating relatively large sideways accelerations. As the sideways leap is made there is an upwards, vertical acceleration as the subject jumps up from the ground and sharp vertical decelerations as the subject lands. In the over-under barrier task, the subject was required to duck under and step over three evenly spaced obstacles. Figure 2 d) shows one over-under pattern, comprising a slow moving upwards and downwards wave. The *z*-axis record indicates that the subject is bending and straightening as he dips under and walks over a barrier. The acceleration patterns for the boulder hop and over-under barrier tasks were generally consistent across subjects, although variations in the subjects' strategies in performing the tasks resulted in some variation in acceleration pattern. For example, in the over-under task, a subject could choose to bend at the waist, resulting in relatively large *z*-axis accelerations, or to bend at the knees resulting in larger vertical accelerations.

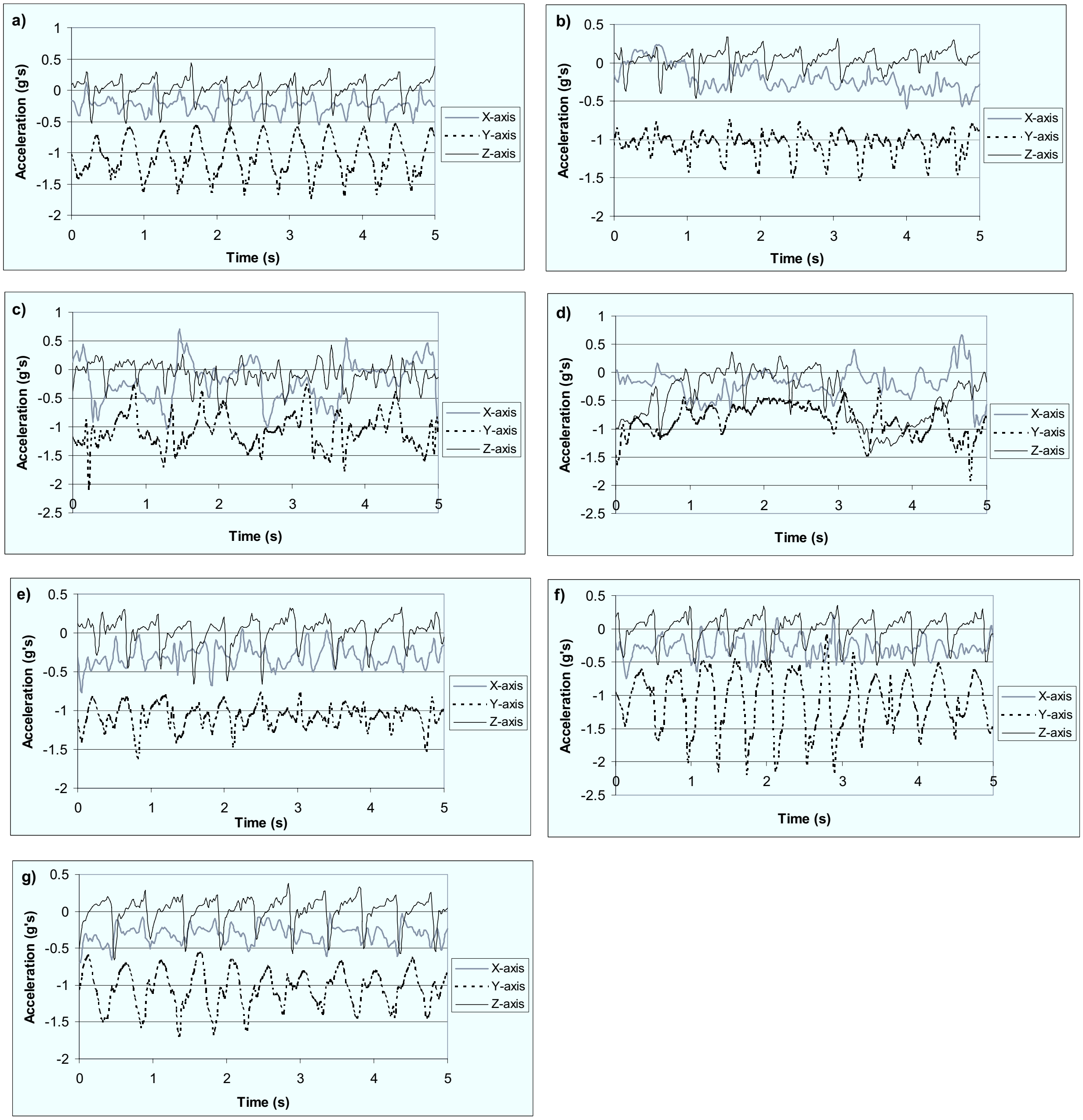
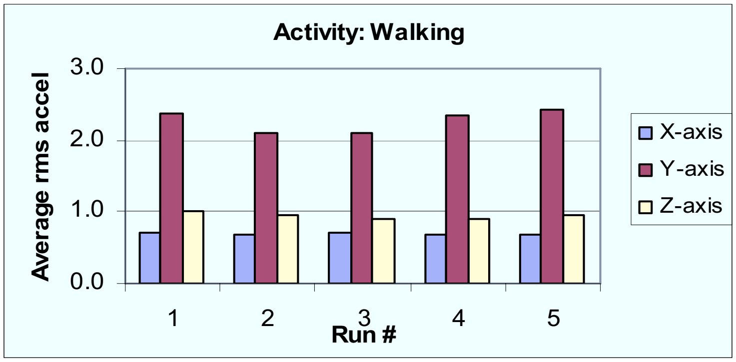


Figure 2: Representative *x*-, *y*- and *z*-axis acceleration patterns for the seven tasks included in the activity circuit (subject: 7MOA, medium load): a) walk; b) balance beam; c) boulder hop; d) over-under barriers; e) slalom run; f) up-down ramp; g) sidehill ramp.

4.2. RMS Analysis

Relative Accelerations on the x-, y- and z-Axes

The root mean square (RMS) value of the acceleration signal was computed for each axis and averaged over the duration of each activity. A representative sample of the average RMS values for one subject and one load condition (subject: 7MOA; medium load) is shown in Figures 3a through 3e. Additional plots for the remaining subjects appear in Appendix C.

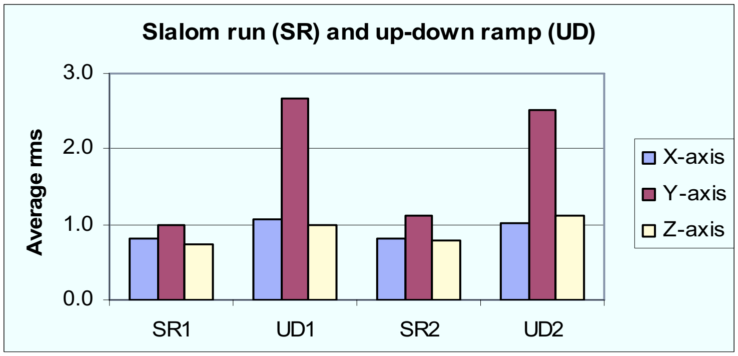


a) Walking

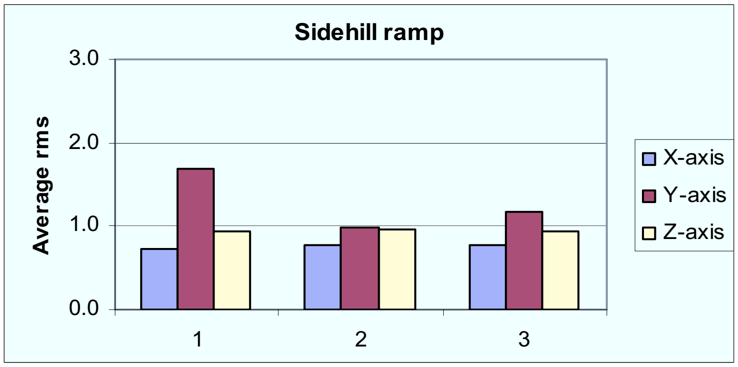
x-axis - Medial/Lateral

y-axis – Vertical

z-axis - Anterior/Posterior

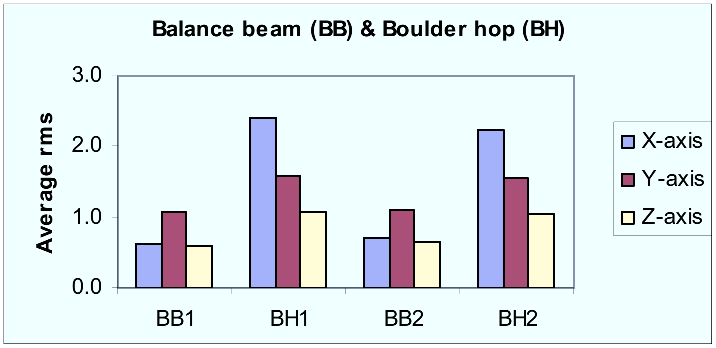


b) Slalom Run and Up-Down Ramp



c) Side hill Ramp

Figure 3: Root Mean Square of Acceleration for different activities.

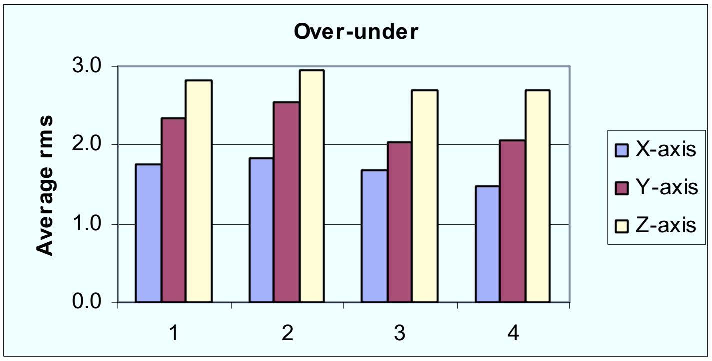


d) Balance Beam and Boulder Hop

X Axis - Medial/Lateral

Y Axis – Vertical

Z Axis - Anterior/Posterior



e) Over / Under Obstacles

Figure 3: (continued) Root Mean Square of the Acceleration for activities requiring large upper body excursions. Note, the balance beam activity has been included; depending on the ability of the subject to maintain balance, there may be large excursions, particularly in the side-to-side direction.

In Figure 3, activities have been grouped into those primarily related to walking motions: (a, b and c) and activities requiring large excursions of the upper body, (d and e). These representative plots are from Subject 7, trial A, medium load.

RMS Acceleration Magnitude

The magnitude of the average RMS acceleration values was calculated using the formula:

$$\left|RMS\right| = \sqrt{x_{rms}^2 + y_{rms}^2 + z_{rms}^2}$$

This gives the overall RMS vector magnitude across the three axes. The magnitudes were averaged across subjects for each repetition of the seven activities and each load condition. The average magnitudes and standard deviations are summarized in Table 3

Table 3: Summary of RMS Magnitudes

Activity	**BO Subjects (n = 3)**		**MO Subjects (n=7)**					
			Light Load		**Medium Load**		**Heavy Load**	
	Avg	Std dev	Avg	Std dev	Avg	Std dev	Avg	Std dev
W/R 1	**9.446**	**1.393**	**2.693**	**0.661**	**2.583**	**0.559**	**2.572**	**0.496**
BB 1	4.967	2.619	2.014	0.400	1.744	0.285	1.708	0.169
BH 1	7.079	1.087	4.058	0.683	3.425	0.528	3.606	0.456
BB 2	3.740	2.871	2.000	0.265	1.863	0.270	1.822	0.274
BH 2	6.817	1.192	3.925	0.666	3.565	0.526	3.615	0.553
W/R 2	**9.367**	**1.264**	**2.784**	**0.639**	**2.615**	**0.494**	**2.660**	**0.437**
O-U 1	7.024	0.651	3.888	0.819	3.772	0.393	3.526	0.355
O-U 2	7.417	0.563	3.872	0.804	3.694	0.381	3.510	0.352
O-U 3	6.998	0.620	3.879	0.735	3.784	0.505	3.577	0.407
O-U 4	7.220	0.913	3.848	0.647	3.770	0.453	3.555	0.289
W/R 3	**8.890**	**1.598**	**2.782**	**0.570**	**2.615**	**0.575**	**2.648**	**0.452**
SH 1	7.324	0.801	2.355	0.367	2.101	0.563	2.121	0.330
U-D 1	8.652	1.105	3.214	0.490	3.194	0.571	2.899	0.238
SH 2	7.188	1.336	2.176	0.321	2.099	0.465	2.048	0.368
U-D 2	8.278	1.116	3.141	0.425	3.169	0.541	2.810	0.312
W/R 4	**8.719**	**1.914**	**2.757**	**0.680**	**2.645**	**0.646**	**2.703**	**0.462**
S-R 1	7.425	0.782	2.476	0.541	2.346	0.654	2.334	0.392
S-R 2	7.701	1.069	2.570	0.606	2.365	0.715	2.335	0.452
S-R 3	7.788	1.354	2.462	0.555	2.322	0.662	2.310	0.523
W/R 5	**8.735**	**1.934**	**2.746**	**0.666**	**2.642**	**0.689**	**2.698**	**0.479**

Activities: W/R=walk or run; BB=balance beam; BH=boulder hop; O-U=over-under; SH=slalom run; U-D=up-down ramp; S-R=sidehill ramp

The average magnitude was plotted for each activity and each load condition, as shown in Figure 4 and Figure 5. In the BO case, running was the highest intensity activity, i.e. it involved the highest acceleration levels. Going over the up and down ramp exhibited the next highest acceleration levels. Several tasks are clustered at comparable RMS acceleration magnitudes, indicating that the level of activity for these tasks is comparable. Lastly the balance beam had the lowest RMS acceleration magnitude, likely because the subjects needed to slow down to perform this high agility task.

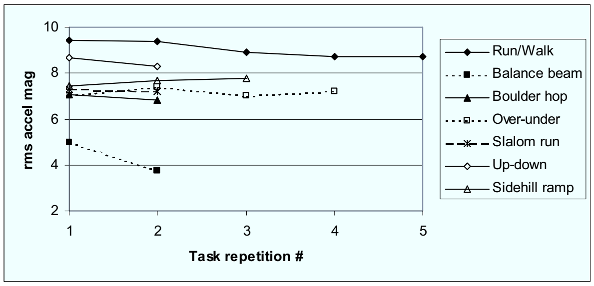


Figure 4: Average magnitude of RMS accelerations for BO subjects.

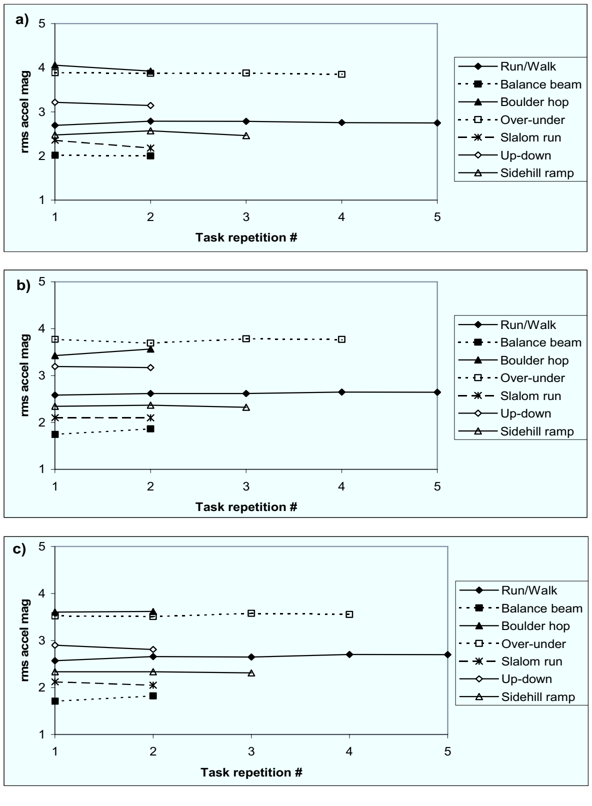


Figure 5: Average magnitude of RMS accelerations for MO subjects: a) light load; b)medium load; c) heavy load

The RMS acceleration magnitudes are considerably lower for the MO subjects, suggesting that walking is a much lower intensity activity than running. The tasks are also grouped differently on the plot, with three tasks having higher RMS acceleration magnitudes (the boulder hop, over-under barrier and up-down ramp tasks) and three tasks having lower RMS acceleration magnitudes (the sidehill ramp, slalom run and balance beam tasks) than the walking task. This pattern is consistent across the three load levels. There is a slight decrease in the magnitude of RMS acceleration with load for all tasks.

These results suggest that whole body accelerations measured in humans can be separated into high intensity tasks (tasks resulting in higher overall accelerations than level walking) and low intensity tasks. A measure of whole body acceleration during level walking and running would be required for individual subjects, in order to set a 'walking' baseline and maximum acceleration level, respectively.

RMS Statistics

From visual inspection of the results of the average RMS acceleration calculations, it was felt that the pattern of relative activity in the *x*-, *y*- and *z*-axes is distinctive for each task performed and, in general, consistent across subjects. To get a measure of the relative contribution of the accelerations on the three axes, the ratio of the average RMS acceleration on the *x*-axis and *z*-axis to the average RMS acceleration on the *y*-axis – the X/Y or mediolateral:vertical ratio and Z/Y or anteroposterior:vertical ratio – were calculated. The X/Y and Z/Y ratios for all MO subjects were grouped by activity; for each load, n=35 for walk; n=14 for balance beam, boulder hop, slalom run and up-down ramp; n=28 for over-under; and n=21 for sidehill ramp. The mean value and standard deviations of the ratios were computed and are given in Table 4 and the mean values of the ratios are plotted in Figure 6.

Table 4. Average RMS Acceleration X/Y and Z/Y Ratios.

	Light load		**Medium load**		**Heavy load**	
X/Y ratios	**Average**	**Std dev**	**Average**	**Std dev**	**Average**	**Std dev**
Walk	0.3661	0.0467	0.3651	0.0448	0.3578	0.0426
Bal beam	0.6475	0.2417	0.5667	0.1017	0.6625	0.2038
B-hop	1.0531	0.4112	1.1434	0.3334	0.9597	0.3381
Over-under	0.9657	0.2210	0.9047	0.2285	0.9283	0.1893
Slalom	0.5938	0.0723	0.6196	0.0938	0.6462	0.1343
Up-down	0.4165	0.0607	0.4107	0.0739	0.4320	0.0779
Sidehill	0.4814	0.0582	0.4909	0.1016	0.4915	0.0575
Z/Y ratios						
Walk	0.4952	0.0497	0.4906	0.0994	0.4853	0.0804
Bal beam	0.5932	0.0555	0.6086	0.0964	0.6346	0.1140
B-hop	0.7043	0.3270	0.6852	0.2237	0.6358	0.1724
Over-under	1.2801	0.2172	1.2517	0.2704	1.2356	0.2069
Slalom	0.6127	0.0769	0.6030	0.1117	0.6624	0.1328
Up-down	0.6139	0.1417	0.6154	0.2138	0.5988	0.1772
Sidehill	0.5816	0.0671	0.6260	0.1458	0.6046	0.0937

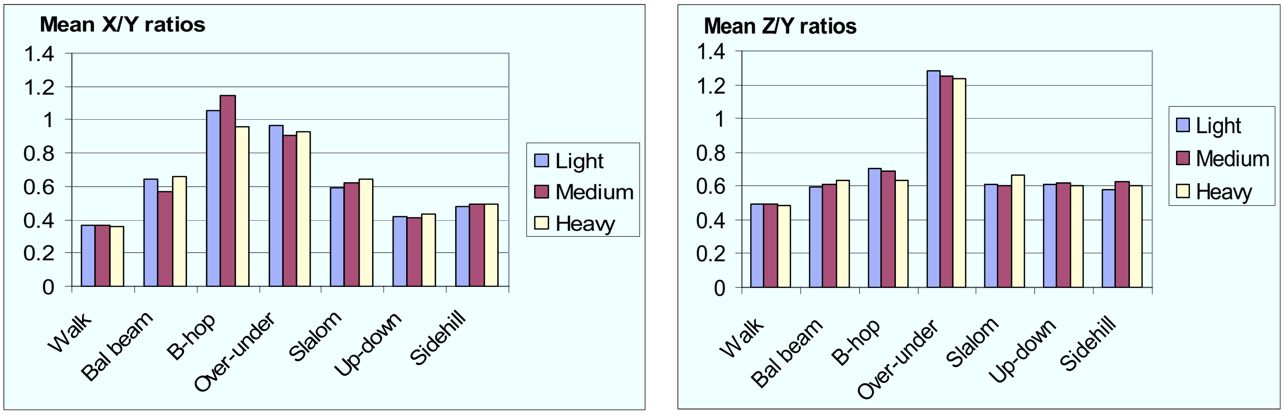


Figure 6: Mean X/Y and Z/Y ratios of the average RMS acceleration values, grouped by activity.

The X/Y and Z/Y ratios were analyzed using a single factor ANOVA, to determine if there is a significant difference in mean values and distributions across task and across load. To evaluate the task effect, data were grouped by load and the ANOVA was run for each of the three loads; to evaluate the load effect, data were grouped by task and the ANOVA was run for each of the seven tasks. The P-values obtained for each test are given in Tables 5 and 6.

Table 5: Single Factor ANOVA of RMS Across Activities

Variation with Activity for:	P-value: X/Y	P-value: Z/Y
Light load	<.001	<.001
Medium load	<.001	<.001
Heavy load	<.001	<.001

Table 6: Single Factor ANOVA of RMS Across Loads

Variation with Load for:	P-value X/Y	P-value Z/Y
Walk	0.7002	0.8728
Balance beam	0.3731	0.4905
Boulder hop	0.4155	0.7564
Over-under	0.5621	0.7702
Slalom run	0.4140	0.3166
Up-down ramp	0.7179	0.9643
Sidehill ramp	0.8885	0.4122

These results clearly show that the ratios vary significantly across tasks, but do not vary across loads.

4.3. Metabolic Energy Cost Analysis

Heart rate and Percent $M\dot{V}O_2$

Prior to participating in the study, each subject was required to perform a maximal effort shuttle run test to provide a baseline fitness standard. This testing was conducted not more than 3 weeks prior to participating in the study. The maximal heart rate and maximum $\dot{V}O_2$ ($M\dot{V}O_2$) was determined for each subject. Using this value the percent maximum $\dot{V}O_2$ ($\%M\dot{V}O_2$) can be calculated using the following formula:

$$100 \times \left(\frac{\text{Current Heart Rate} - \text{Resting Heart Rate}}{\text{Maximal Heart Rate} - \text{Resting Heart Rate}} \right) = \%M\dot{V}O_2$$

During performance of the test circuit, heart rate was measured with a Polar® Heart monitor and reported verbally by the subjects at the completion of each lap and each activity station. $\%M\dot{V}O_2$ was calculated from the reported heart rates and examined to determine if it was correlated to load carried and activity.

Percent $M\dot{V}O_2$ versus Load Carried and Activity

Percent $M\dot{V}O_2$ for all subjects, during all activities (walking plus stations) was compared across all loads carried. Correlation coefficients of 0.90 and 0.95 respectively were found for the two different packs tested, indicating a good correlation between $\%M\dot{V}O_2$ and load carried. This concurs with previous physiological studies (e.g. Holewijn, 2000). These data are summarized in Table 7.

Table 7: Correlation of Percent $M\dot{V}O_2$ to the Load Carried for Multiple Activities

Load Carried (kg)	CTS Pack Avg %MVO2	Correlation Coefficient	DFS Pack Avg %MVO2	Correlation Coefficient
10.00	58.12	**0.90**	53.13	**0.95**
20.00	59.90		54.75	
23.90	60.20		56.75	
30.00	64.94		60.73	

When $\%M\dot{V}O_2$ versus load was examined for walking only, the correlation coefficients decreased. The data are plotted in Figure 7 and the reason for the decrease becomes apparent. One data point in the data for the Dynamic Framesheet© (DFS) pack appears anomalous[10]. If this point is not included in the data, $\%M\dot{V}O_2$ correlations with load carried while walking are 0.97 and >0.99 respectively.

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[10] The DFS pack used a spring system to control the motion between the load volume and the pack suspension system (shoulder straps and waist belt). The springs used for the medium load were better matched to the mass of the load than the springs used for the other loads, optimizing the displacement of the load volume with respect to the suspension system.

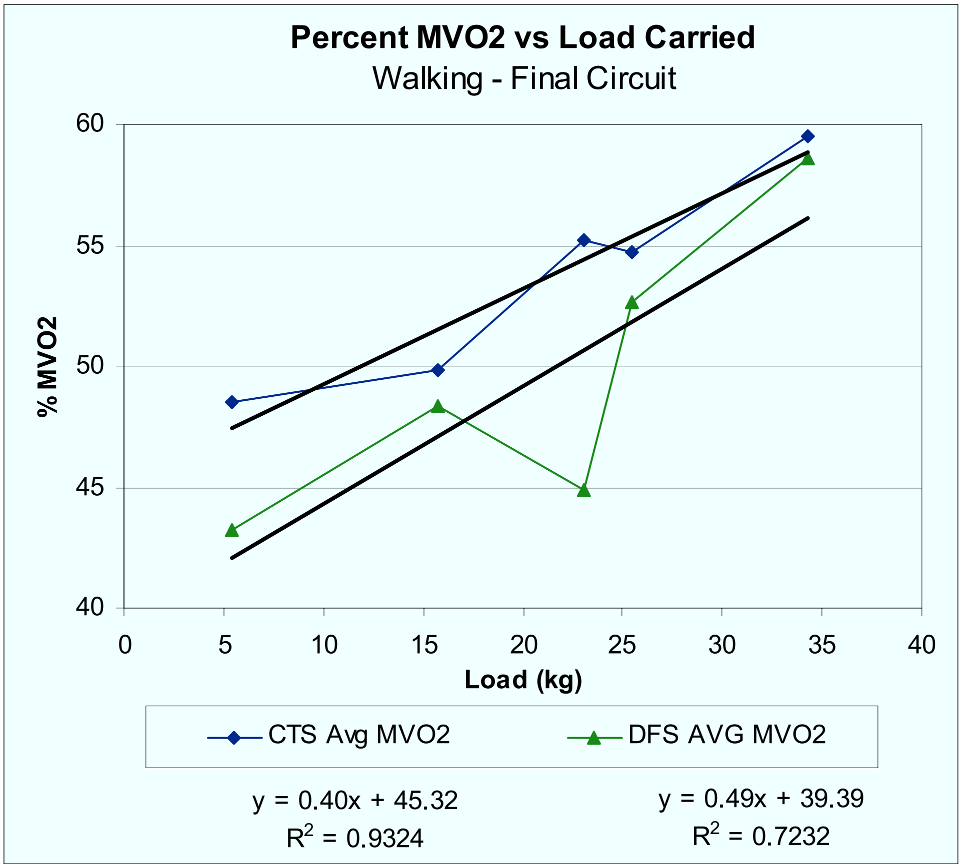

Figure 7: Percent MVO_2 versus Load Carried While Walking. CTS refers to the Canadian Clothe the Soldier Pack, DFS refers to the Dynamic Framesheet™.

Percent $M\dot{V}O_2$ for all subjects wearing both packs, was compared across all activity stations. $\% M\dot{V}O_2$ was separated by load condition to avoid the compounding effect of load established in section 4.3.2. The $\% M\dot{V}O_2$ values were calculated from subject HR recorded immediately upon completion of each activity station. Data from seven trials involving five subjects were grouped and analysed using in a single factor ANOVA, and the results appear in Table **8.**

Table 8 ANOVA of MVO2 across 5 Activity Stations: walking 10 laps; balance beam/boulder hop; over-under/fence climb; slalom run/up-down ramp and sidehill ramp. $\alpha = 0.05$

Variation with activity for:	P-value
Light load	0.1242
Medium load	0.0724
Heavy load	0.0627

The results of the ANOVA indicate that $\% M\dot{V}O_2$ does not vary significantly across activity stations, and that $\% M\dot{V}O_2$ estimated from HR, alone, is insufficient to differentiate between activities. Additional information, such as that available from the upper body acceleration record, is needed to differentiate the EE required to perform specific activities.

Acceleration Power versus Load Carried

Acceleration data analysis was performed using a combination of MicroSoft Excel and custom written collation and analysis software (CoAn™) based on the MatLab® and Labview® platforms. CoAn allows the user to select a portion of data for analysis, or it can automatically input data files and then parse the data into activities based on a user provided time stamped data file. As well, data files can be read and a user can preview the data. CoAn computes:

1. Signal RMS values on the *x*-, *y*- and *z*-axes
2. Signal power on the *x*-, *y*- and *z*-axes and total signal power
3. Signal power spectra for the *x*-, *y*- and *z*-axes for the individual activity stations
4. Signal mean frequency for the *x*-, *y*- and *z*-axes.

Signal power is defined as the integral of the squared acceleration signal over time and total power is the vector sum of the three orthogonal acceleration powers.

CoAn is capable of handling any signal data captured on the Embla recorder. The user has full control over any scale factors and offset voltages to be applied to the data to permit the RMS, power, spectral analysis and mean frequency analyses to be tailored to a signal type. Additionally, this platform will allow the addition of other types of analysis as they are required. The CoAn software is included in Appendix E.

Using the signal power calculated by CoAn, the relationship between power in the accelerometer signal and load carried was examined. Power was summed across all activities and all subjects and plotted versus load as shown in Figure 8.

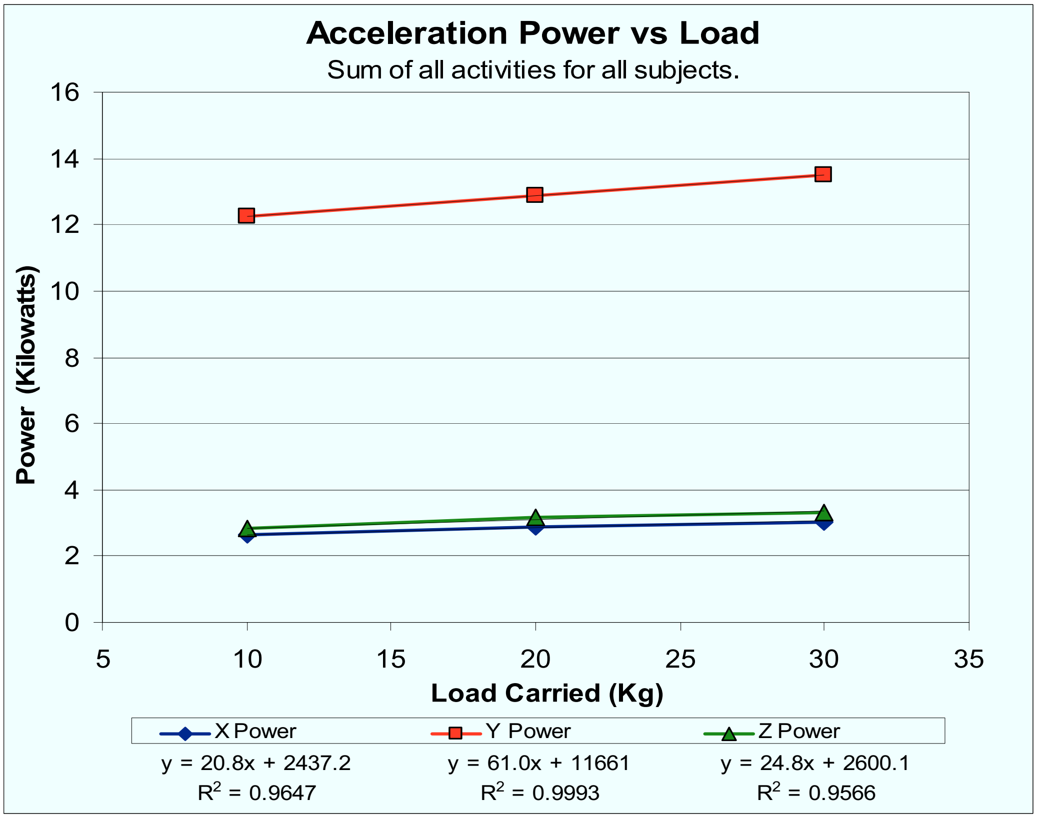

Figure 8: Acceleration Power versus Load Carried. The *y*-axis corresponds to vertical motion while *x* and *z* correspond to mediolateral and anteroposterior motion respectively.

A single factor ANOVA analysis on the accelerometer signal power yielded the p-values shown in Table 8. These values indicate that power, on all axes, is strongly correlated with load, across all activities.

Table 8: Single Factor ANOVA, Acceleration Across all Activities

P-values	Heavy Load	Medium Load	Light Load
X Power	<0.001	<0.001	<0.001
Y Power	<0.001	<0.001	<0.001
Z Power	<0.001	<0.001	<0.001
R Power*	<0.001	<0.001	<0.001

$* \text{R Power} = \sqrt{\text{X Power}^2 + \text{Y Power}^2 + \text{Z Power}^2}$

Acceleration Spectral Power versus Load Carried

Power in the acceleration signal can also be obtained by integrating over the power spectral density (PSD) of the signal. A 128-point PSD was computed in CoAn for each lap and activity station. Since the data were sampled at 50 Hz, the range of frequencies in the PSD is 0-25 Hz, giving a frequency resolution of 0.1953Hz. A set of PSD's for the first and last walk around the perimeter (lap 1 and lap 10) and each of the activity stations, from a single subject, is shown in Figure 9. From this figure, it is apparent that there is a characteristic *walking frequency*, which appears in the *y*-axis data from lap 1 and lap 10, and also in the PSD's for station #3 and station #4. In other words, the vertical acceleration associated with walking follows a nearly sinusoidal pattern (this is apparent in Figure 2) and the fundamental frequency is at the step frequency. Given this characteristic frequency, it was decided to compute the power in three bins: frequencies less than the walking frequency; walking frequency; and frequencies above the walking frequency. For the walking frequency, a bin which included the peak frequency was defined for each data set – the bin extended from a low cut-off frequency ω_L to a high cut-off frequency ω_H. The first inflection point on the PSD preceding the peak walking frequency was defined as ω_L while first inflection point above the walking frequency peak was defined as ω_H. The low frequency bin was defined from zero to ω_L and the high frequency bin extended from ω_H to 25 Hz. Two power ratios were calculated; low frequency power**:**walking frequency power, and high frequency power**:**walking frequency power, P_L/P_W and P_H/P_W respectively. A single factor ANOVA, ($\alpha = 0.05$) was performed to examine the effect of load on these power ratios. Results are summarized in Table 9. None of the power ratios was correlated to the load carried.

Table 9: Single Factor ANOVA, Spectral Power Across all Activities versus Load

Power Ratio	**P-values**		**Power Ratio**	**P-values**
P_{LX}/P_W	0.370		P_{HX}/P_W	0.881
P_{LY}/P_W	0.239		P_{HY}/P_W	0.764
P_{LZ}/P_W	0.186		P_{HZ}/P_W	0.245

Acceleration Spectral Power versus Activity

Power spectral density ratios, P_L/P_W and P_H/P_W were compared across the four stations and walking. A single factor ANOVA, ($\alpha = 0.05$), was performed and the results are summarized in Table 10. The P_L/P_W ratio in the *y* and *z* axes were correlated to activity across all loads carried. When examined in terms of the physical system, this means that the magnitude and the amount of lower frequency content in the power spectrum of both the vertical and anteroposterior accelerations was related to activity. The low frequency content of acceleration in the mediolateral direction was not correlated. This was consistent regardless of the load carried. The P_H/P_W ratio on all three axes was correlated to activity and across all loads. The higher frequency torso accelerations in the vertical, anteroposterior and mediolateral axes was effected by the nature of the activity and this effect was discernable while carrying light, medium or heavy loads. A post hoc test is required to determine which specific activities were correlated with an increase in power at the higher frequencies.

Table 10: Single Factor ANOVA, Spectral Power versus Station

Power Ratio Low/Walk	**Load Carried**	**P-values**		**Power Ratio High/Walk**	**Load Carried**	**P-values**
P_{LX}/P_W	Light	0.112955		P_{HX}/P_W	Light	**< 0.001**
P_{LY}/P_W	Light	**< 0.001**		P_{HY}/P_W	Light	**< 0.001**
P_{LZ}/P_W	Light	**< 0.001**		P_{HZ}/P_W	Light	**0.0116**
P_{LX}/P_W	Medium	0.063336		P_{HX}/P_W	Medium	**< 0.001**
P_{LY}/P_W	Medium	**< 0.001**		P_{HY}/P_W	Medium	**< 0.001**
P_{LZ}/P_W	Medium	**< 0.001**		P_{HZ}/P_W	Medium	**< 0.001**
P_{LX}/P_W	Heavy	0.309782		P_{HX}/P_W	Heavy	**0.0138**
P_{LY}/P_W	Heavy	**< 0.001**		P_{HY}/P_W	Heavy	**< 0.001**
P_{LZ}/P_W	Heavy	**< 0.001**		P_{HZ}/P_W	Heavy	**0.0014**

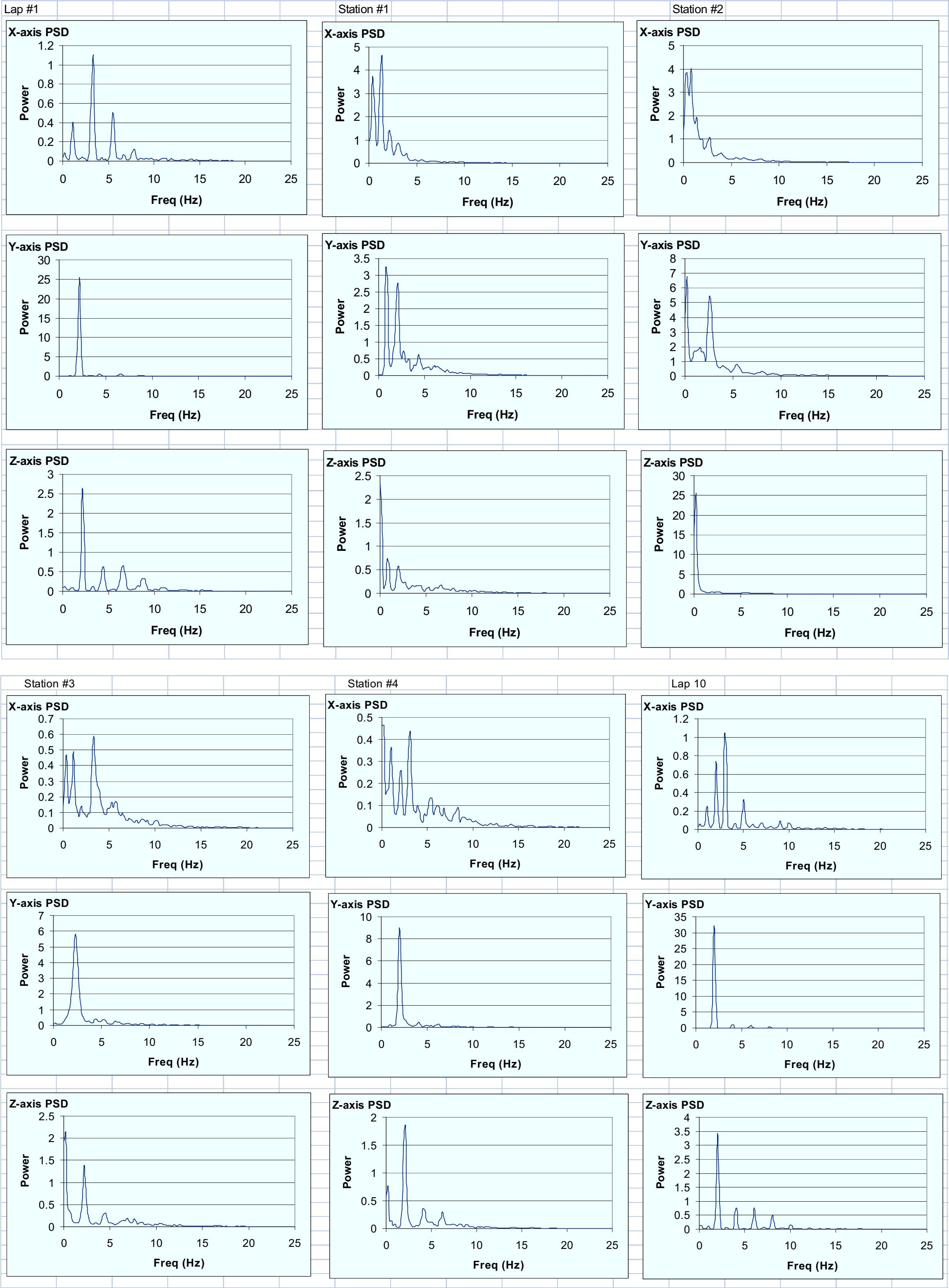

Figure 9: Representative PSD's for lap 1, station 1, station 2, station 3, station 4 and lap 10 from subject 7MOA – medium load. Stations are defined in Table 2.

4.4. Spectral Analysis by Activity

To further characterize the motion patterns revealed by upper body accelerations recorded during specific movements, the PSD was calculated for each performance of the defined tasks of the activity circuit: walking, balance beam, boulder hop, over-under barriers, slalom run, up-down ramp and sidehill ramp. Acceleration data recorded for each of the activity stations were analysed for spectral content. To maximize the amount of data included in each spectral estimate, 1024-point PSD's were computed for the walking tasks; and 256-point PSD's were computed for all other tasks. A program was written in Matlab® to compute the PSD's on each axis and to determine the total power in the signal on each axis (x-, y- and z-) by integrating over the PSD. Representative spectra from subject 7MOA, carrying a medium load are shown in Figure 10.

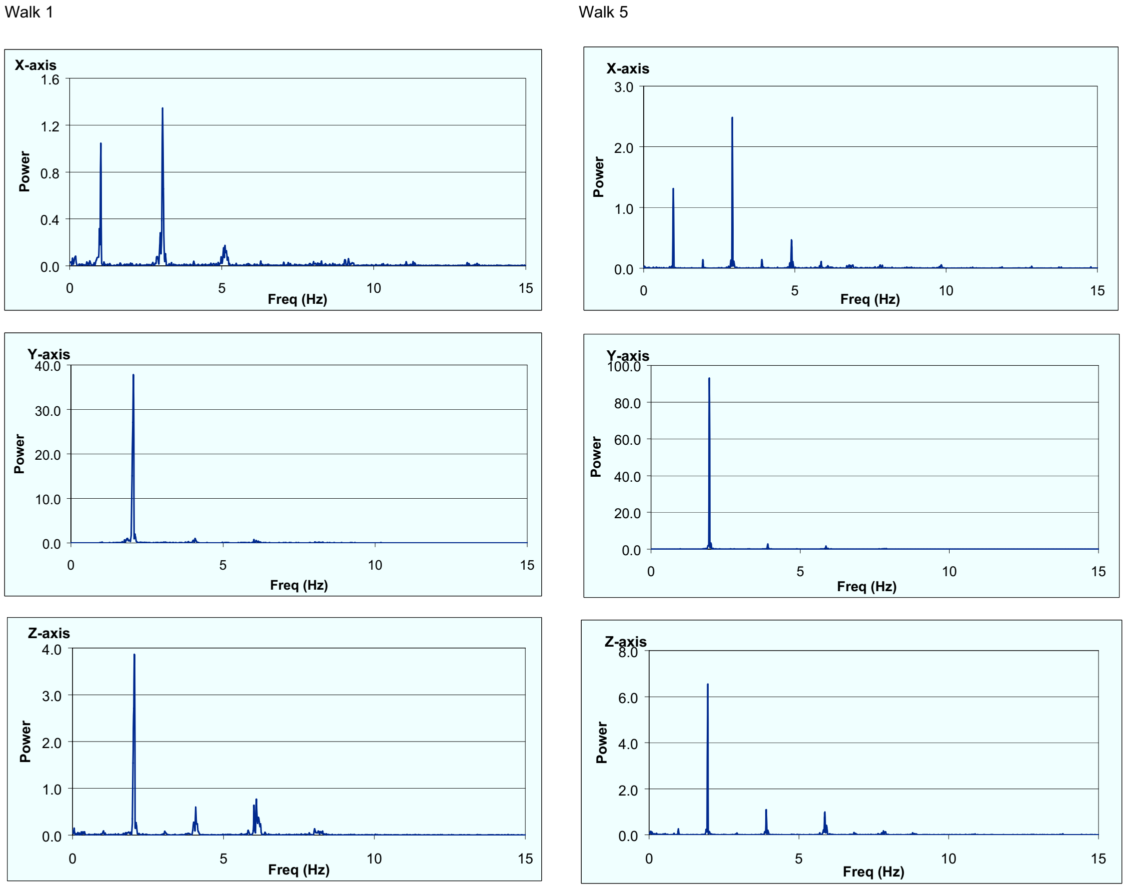

Figure 10(a): PSD's for walk 1 and walk 5 from subject 7MO carrying a medium load. Spectra are plotted from 0-15 Hz, since the power above 15 Hz is negligible. Note the definite *walking frequency* peak on the vertical (y-) and anteroposterior (z-) axes. These peaks occur at 2.05 and 1.96 Hz for walk 1 and walk 5 respectively.

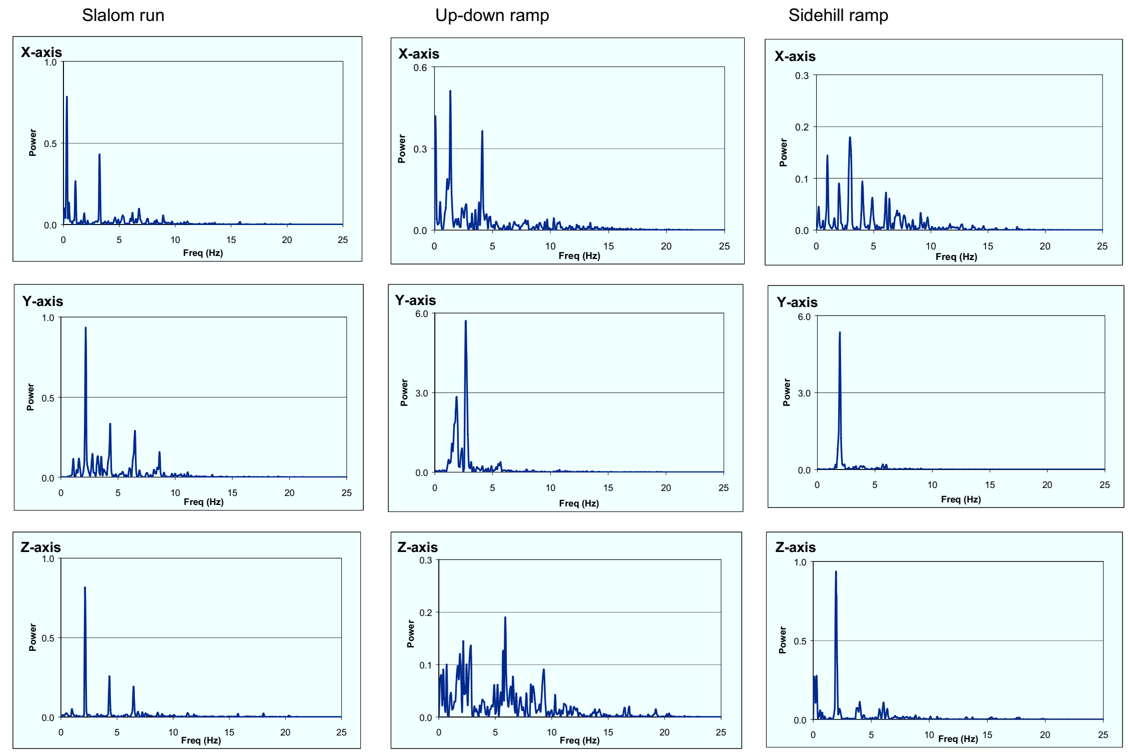

Figure 10(b): PSD's for the mobility activities (slalom run, up-down ramp and sidehill ramp) from subject 7MO carrying a medium load.

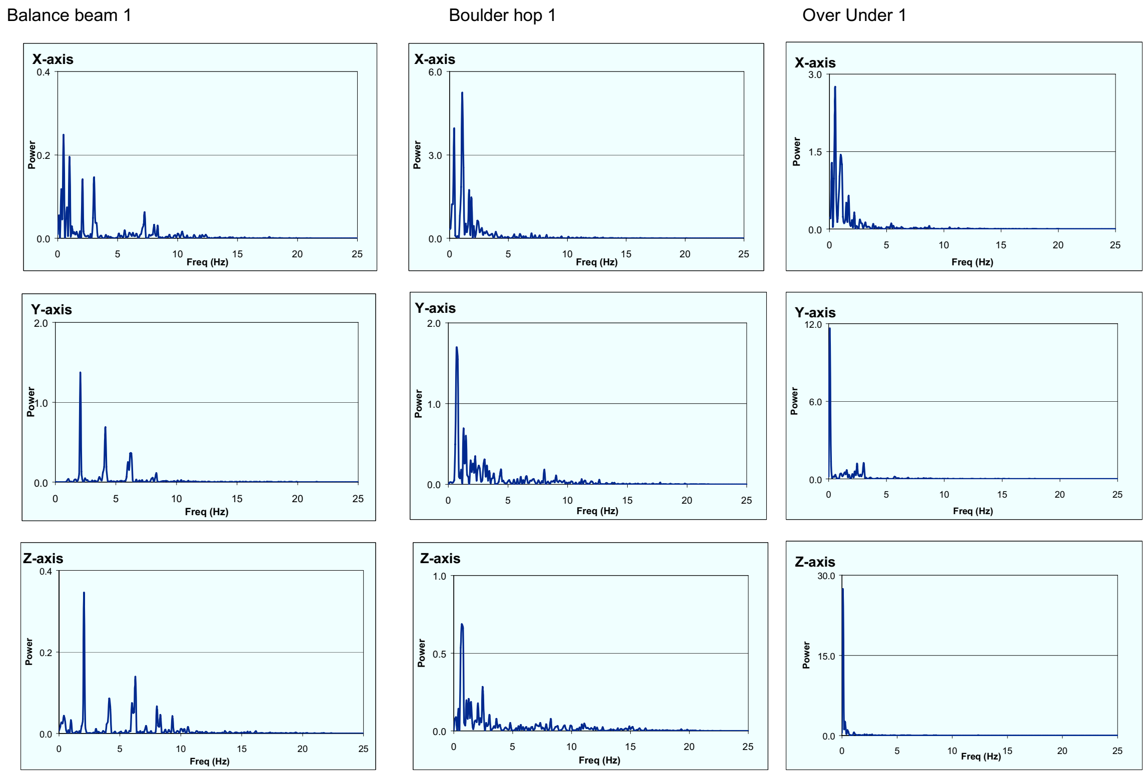

Figure 10(c): PSD's for activities involving more upper body motion (balance beam, boulder hop, over-under) from subject MO carrying a medium load.

As with the activity stations, the signal power is concentrated below 10Hz. In the spectra from walk 1 and walk 5, the single dominant frequency in the *y*-axis spectrum is apparent. There are at least three significant peaks in the spectra obtained from the *x*- and *z*-axis records. The peak frequencies on each axis for each walking activity, for the light medium and heavy loads, performed by subject 7MO are given in Table 11.

Table 11: Peak frequency values for walking activities

Load		**Peak Frequencies (in Hz)**				
Light		**Walk 1**	**Walk 2**	**Walk 3**	**Walk 4**	**Walk 5**
***x*-axis**	Peak 1	0.98	1.03	1.03	1.03	1.03
	Peak 2	3.08	3.05	3.05	3.05	3.03
	Peak 3	5.08	5.08	5.13	5.20	5.08
***y*-axis**		2.05	2.03	2.03	2.05	2.05
***z*-axis**	Peak 1	2.05	2.03	2.03	2.05	2.05
	Peak 2	4.10	4.08	4.08	4.08	4.06
	Peak 3	6.11	6.11	6.16	6.26	6.23
Medium		**Walk 1**	**Walk 2**	**Walk 3**	**Walk 4**	**Walk 5**
***x*-axis**	Peak 1	1.03	1.05	1.05	0.98	0.98
	Peak 2	3.05	3.01	3.01	2.93	2.93
	Peak 3	5.11	5.3	5.23	4.96	4.89
***y*-axis**		2.05	2.03	2.1	1.96	1.96
***z*-axis**	Peak 1	2.05	2.03	2.01	1.96	1.96
	Peak 2	4.08	4.06	4.23	3.98	3.91
	Peak 3	6.09	6.13	6.30	5.94	5.87
Heavy		**Walk 1**	**Walk 2**	**Walk 3**	**Walk 4**	**Walk 5**
***x*-axis**	Peak 1	1.12	1.05	1.03	1.00	1.00
	Peak 2	3.27	3.13	3.13	3.05	3.01
	Peak 3	5.45	5.25	5.18	5.11	5.01
***y*-axis**		2.20	2.08	2.08	2.03	2.00
***z*-axis**	Peak 1	2.25	2.08	2.08	2.03	2.00
	Peak 2	4.55	4.18	4.23	4.10	4.01
	Peak 3	6.50	6.26	6.26	6.10	6.04

The mean peak frequency on the *y*-axis or the *walking frequency* is at 2.04 Hz (S.D = 0.01) for the light load, 2.02 Hz (S.D. = 0.05) for the medium load and 2.08 Hz (S.D. = 0.07) for the heavy load; the power in the PSD is concentrated at this frequency. The first peak in the *x*-axis spectrum occurs at half the walking frequency, reflecting the side to side motion of the body as the centre of gravity moves to be over the foot which is planted on the ground. The other peaks in the *x*-axis record occur at the 3rd and 5th harmonics, indicating that the pattern of motion is periodic but not sinusoidal. Close examination of figure 2(a) reveals that the *x*-axis pattern approaches that of a square wave, and thus the appearance of the fundamental plus 3rd and 5th harmonics in the spectrum is not surprising. The fundamental frequency in the *z*-axis spectra is at the walking frequency with peaks at the 2nd and 3rd harmonics. Again, this indicates that the *z*-axis acceleration pattern is periodic but not sinusoidal. There is little variation in the peak frequencies with load, indicating that carrying loads did not alter the subject's stride rate or pattern of motion. For the medium and heavy loads, the *y*-axis peak frequency – or walking frequency – declined from walk 1 to walk 5, indicating that the subject did slow his pace over the course of the trial.

There are large variations in the spectral patterns for the different tasks. The tasks which primarily involve upright mobility exhibit the dominant walking frequency on the *y*-axis. The patterns are more variable on the *x*- and *z*-axes. The patterns vary considerably for the upper body motion activities where, except for the balance beam task, the walking frequency is not apparent. In the over-under spectra, the very low frequency power is indicative of the low frequency accelerations due to bending and straightening at the waist as the subject stoops under and steps over the barriers respectively.

The PSD's for running were examined from subject 1BO in order to determine how the fundamental frequencies in the acceleration signal change from the walking condition. The values are given in Table 12. It is clear that the pattern of the PSD's for running is similar to that for walking, with three distinctive peaks in the *x*- and *z*-axis spectra and a single dominant frequency in the *y*-axis spectrum. The peak frequencies however are shifted upward, which is indicative of the increased speed of running with respect to walking. The mean *running frequency* for subject 1BO is 2.9 Hz (S.D. = 0.02).

Table 12: Peak frequency values for running activities

Run #	**1**	**2**	**3**	**4**	**5**
***x*-axis**	1.47	1.42	1.42	1.47	1.47
	2.94	2.89	2.89	2.89	2.94
	4.40	4.31	4.31	4.35	4.40
***y*-axis**	**2.94**	**2.89**	**2.89**	**2.89**	**2.94**
***z*-axis**	2.94	2.89	2.89	2.89	2.94
	4.40	4.31	4.31	4.31	4.40
	5.87	5.77	5.72	5.82	5.87

The total power in the acceleration signals for each axis, as well as the overall total power was calculated by integrating over the PSD's. These values for all MO subjects and all task repetitions were grouped and average powers were calculated. The results are shown in Figure 11. Walking and the mobility activities have characteristic patterns with the highest power in the *y*-axis signal and, generally, the least power in the *x*-axis signal. The balance beam activity has a similar pattern. The boulder hop pattern is more variable, with relatively more power in the *x*-axis signal, and the over-under activity has high power on the *z*-axis. The overall power in the acceleration signals, follows the same pattern as the average RMS magnitudes (Section 4.2) with the boulder hop, over under barriers and up-down ramp activities having higher average power than walking and the sidehill ramp, slalom run and balance beam activities having lower overall power, as shown in Figure 12.

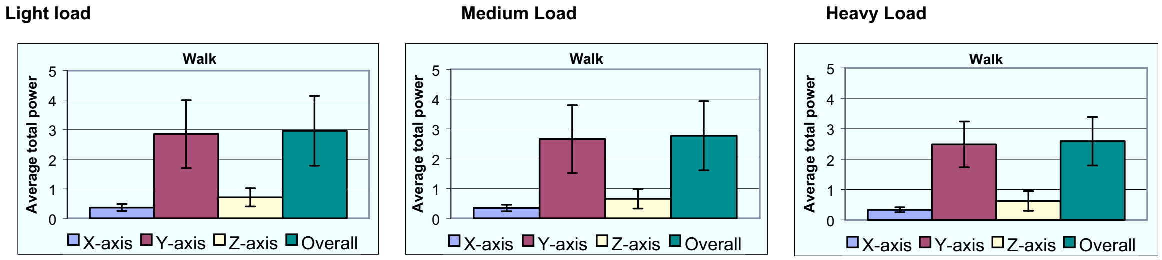

Figure 11(a): Total power in the acceleration signals for the walking activities. The average ±1 standard deviation power is given for all subjects and all walks (n=35). Overall power is calculated as $\sqrt{(X\,\text{power})^2 + (Y\,\text{power})^2 + (Z\,\text{power})^2}$.

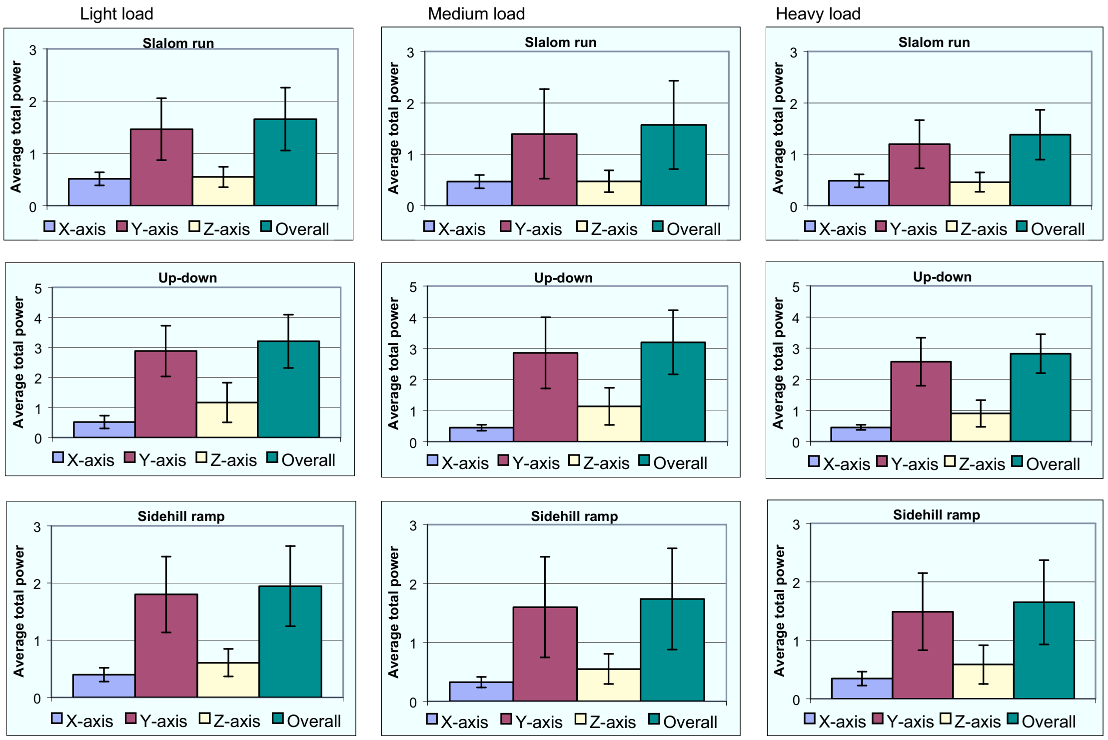

Figure 11(b): Total power in the acceleration signals for the mobility activities (n=14 for slalom run and up-down ramp; n=21 for sidehill ramp).

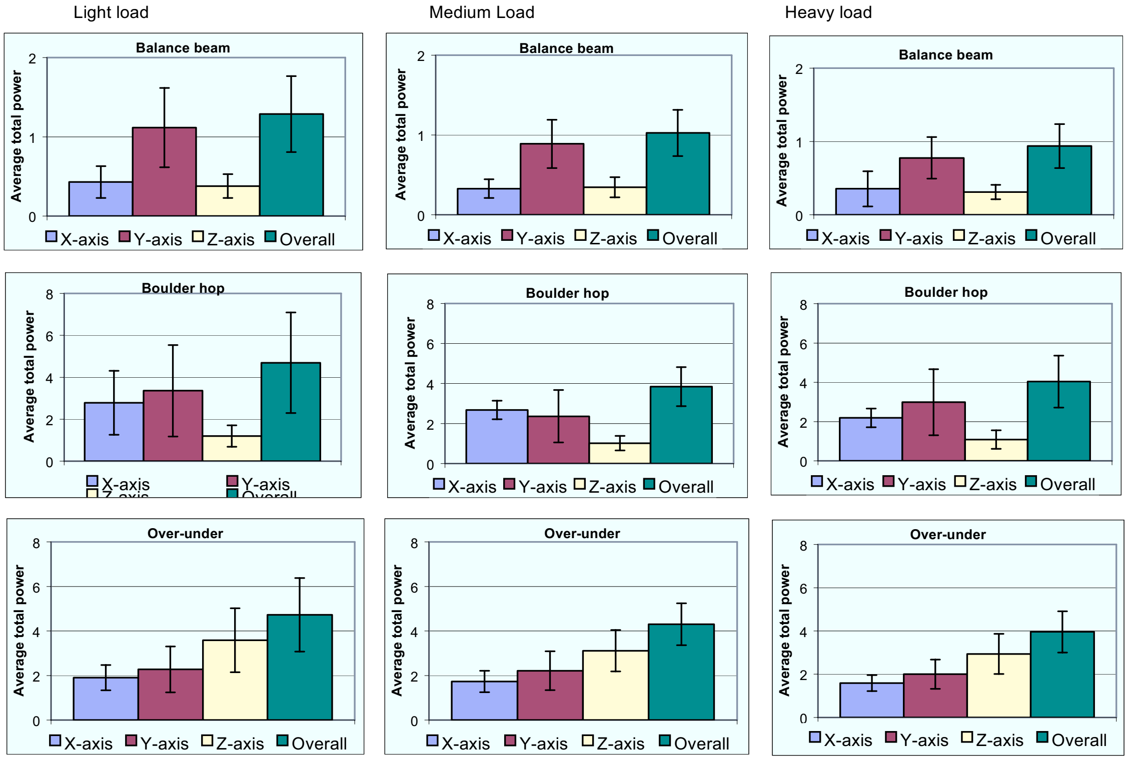

Figure 11(c): Total power in the acceleration signal for activities involving more upper body motion (n=14 for balance beam and boulder hop; n=28 for over-under).

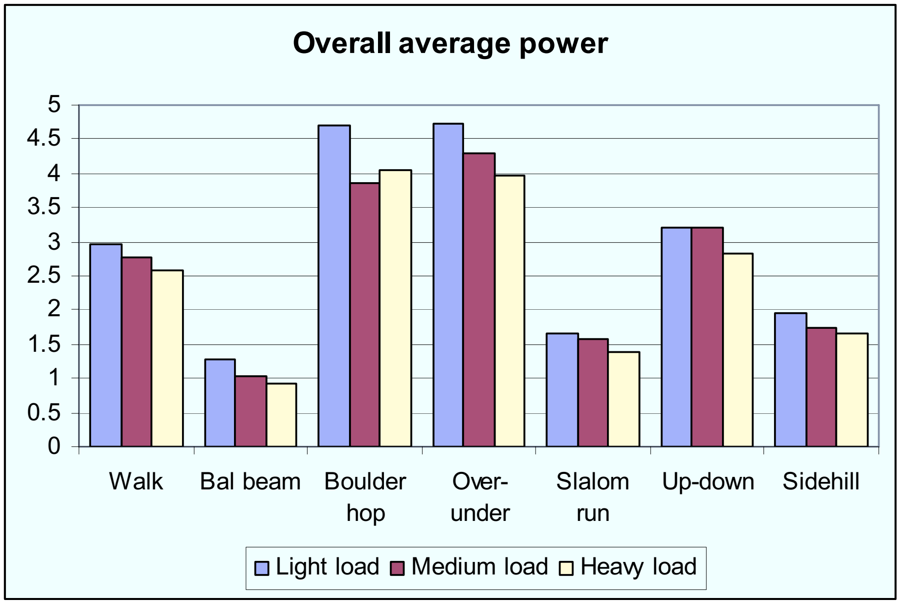

Figure 12: Overall average power versus activity. Data were averaged over all repetitions and all subjects

Variations in the spectral patterns and the spectral power reflect the variations in the subject's actions. Further analysis will be done to determine if the spectral patterns are consistent across subjects. If so, specific spectral parameters of the acceleration signals could be combined with other parameters (e.g. RMS values) to identify the activity, or class of activity, performed by a soldier in the field and provide a profile of activity over the course of a training exercise or other military activity.

5. Conclusions and Recommendations

During the human testing, three types of data were collected: accelerations in three orthogonal directions, heart rate (HR) and strap force data. The acceleration and HR data were extensively analyzed to determine the subject's intensity of activity during performance of the different stations of the test circuit, to determine whether specific activities can be recognized from recorded accelerations and to assess energy expenditure for the various tasks and load conditions. Because of the delicacy of the in-line strap force transducers, strap force data were collected in only a small subset of trials. However, the hardware interface and data collection instrumentation were shown to operate properly and, with more robust transducers, this measurement can be included in future studies.

Previous researchers have established correlations between heart rate and $\%M\dot{V}O_2$ (Li et al., 1993; Murgatroyd et al., 1993). This work has resulted in validated equations and limitations on their application have been established. These standard methodologies were applied to the light, medium, heavy load conditions and the results were examined for correlations between $\%M\dot{V}O_2$ estimated from HR and the load carried. As in previous studies, $\%M\dot{V}O_2$ was found to increase with load carried (Holewijn and Meeuwsen, 2000). However, $\%M\dot{V}O_2$ does not vary significantly across activity stations, suggesting that additional information is needed to differentiate the EE between activities.

Currently, a growing body of work is establishing accelerometry as a useful biomechanical analysis tool. Whole body acceleration histories have been used to estimate mechanical energy costs (Wong et al., 1981; Bouten, et al., 1994; Schutz Y et al., 1996; Bouten et al., 1997; Chen et al., 1997; Hendelman et al., 2000; Welk et al., 2000; Campbell et al., 2002); 3D accelerations have been used to determine the speed, distance and cadence of walking (Herren et al., 1999; Schutz et al., 2002) and specific activities have been detected from a whole body acceleration record (Mäntyjärvi et al., 2001). Other motion sensing devices have been used to measure lower limb kinematics for gait analysis (Miyazaki, 1997; Tong and Granat, 1999). These applications are evolving and methodologies for analysing data are still being developed to suit the different applications.

In this study, the power in the acceleration signals measured on the three axes was computed for performance of the activity circuit – specifically for the walking activities and each of the activity stations. The power, summed over all activities and all subjects, was found to be correlated with load. However, the relative signal power at low frequencies (P_L/P_W) versus signal power at high frequencies (P_H/P_W) was not affected by load carried.

The acceleration signals were also analyzed using other signal characterization strategies, including RMS and spectral analysis. This analysis was done by task: walking, balance beam, boulder hop, over-under, slalom run, up-down ramp and sidehill ramp. The results of the RMS analysis of the recorded acceleration signals indicate that a specific task or a class of tasks (e.g. high, medium and low intensity tasks) can be identified from recorded upper body accelerations. The task intensity, as reflected in the magnitude of the average RMS value, is ranked with respect to the intensity of walking. However, it is apparent from Figures 4 and 5, that the intensity of running is substantially higher than that of walking and that the magnitude of the RMS value for all activities is above that of walking, when the activities are performed at a higher pace. This is consistent with the finding that whole body acceleration signal amplitude increases with speed (Herren et al., 1999; Schutz et al., 2002). Given this result, it will be necessary to determine the speed of an activity, before it is ranked with respect to intensity. Spectral analysis of the acceleration signals by task revealed a distinctive *walking frequency*, evidenced by a large peak in the vertical axis spectrum for the walking activity. For walking, this peak occurs at approximately 2 Hz and increases to approximately 3 Hz for running. It may be possible to use this fundamental frequency as an estimate of speed, and rank the intensity of activity using the fundamental frequency and acceleration signal magnitude.

6. Future Development

6.1. Estimating Energy Expenditure

The Activity Assessment Module has been designed to record electrocardiogram (ECG) signals, as well as accelerations, surface temperature and strap tensions. As noted in the previous report, the ECG channels were not functional at the time of the testing, so HR was monitored using a Polar HR monitor and manually recorded each time the subject passed the start position of the circuit. Since it has been found that using HR combined with accelerations gives a better estimate of energy cost (Luke et al., 1997), the ECG interface will be re-designed so that a continuous record of HR is available during activity monitoring and energy expenditure will be estimated using both HR and body acceleration. The CoAn software will be upgraded to provide these estimates under user control.

It has been reported in the literature that EE can be accurately estimated from whole body accelerations for certain activities, in particular level walking, but that the energy cost of activities such as isometric contractions, arm movement and load bearing is not reliably detected by measuring body acceleration. It is necessary to validate the combined use of HR, body acceleration (whole body and/or upper body) and possibly limb acceleration to reliably estimate energy expenditure during load carriage. Such a validation will be carried out using a treadmill test, where $\% M\dot{V}O_2$ will be measured using indirect calorimetry, simultaneously with HR and body acceleration, while subjects walk at different paces and carrying different loads.

6.2. Task Intensity Profile

The results of this study show that tasks can be ranked according to their intensity with respect to walking and running, using relatively simple signal processing techniques. The CoAn software will be upgraded to provide an Activity Intensity Profile based on an acceleration record obtained over a specified time frame. The profile may also contain an estimate of the speed at which the subject is moving.

6.3. Task Identification

It has been shown that acceleration patterns on the three axes – mediolateral, vertical and anteroposterior – vary with task performed. With more sophisticated analysis tools, e.g. using a neural network classifier, it may be possible to identify specific tasks or classes of tasks (e.g. a jumping versus a walking or running pattern) from an acceleration record.

7. References

Bouten, C.V., Westerterp, K.R., Verduin, M. and Janssen, J.D., "Assessment of energy expenditure for physical activity using a triaxial accelerometer," *Med. Sci, Sports Exerc.*, vol. 26, pp. 1516-1523, 1994.

Bouten C.V., Koekkoek K.T., Verduin M., Kodde R. and Janssen J.D., "A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity", *IEEE Trans. Biomed. Eng.*, vol. 44, pp.136-147, 1997.

Campbell, K.L., Crocker, P.R.E. and McKenzie, D.C., "Field evaluation of energy expenditure in women using Tritrac accelerometers," *Med. Sci. Sports Exerc.*, vol. 34, pp. 1667-1674, 2002.

Chen, K.Y. and Sun, M., "Improving energy expenditure estimation by using a triaxial accelerometer," *J. Appl. Physiol.*, vol. 83, pp. 2112-2122, 1997.

Hendelman, D., Miller, K., Baggett, C., Debold, E. and Freedson, P., "Validity of accelerometry for the assessment of moderate intensity physical activity in the field," *Med. Sci. Sports Exerc.*, vol. 32(9) Suppl., pp. S442-S449, 2000.

Herren, R., Sparti, A., Aminian, K. and Schutz, Y., "The prediction of speed and incline in outdorr running in humans using accelerometry," *Med. Sci. Sports Exerc.*, vol. 31, pp. 1053-1059, 1999.

Holewijn, M. and Meeuwsen, T., "Physiological strain during load carrying: effects of mass and type of backpack," *Proceedings RTO Meeting on Soldier Mobility: Innovations in Load Carriage System Design and Evaluation*, pp. 1.1-1.12, 2000.

Inman, V.T., Ralston, H.J. and Todd, F., *Human Walking, 1st ed.*, Williams & Wilkins, Baltimore, 1981.

Li, R., Deurenberg, P. and Hautvest, J.G.A.J., "A critical evaluation of heart rate monitoring to assess energy expenditure in individuals," *Am. J. Clin. Nutr.*, vol. 58, pp. 602-607, 1993.

Luke, A., Maki, K.C., Barkey, N., Cooper, R. and McGee, D., "Simultaneous monitoring of heart rate and motion to assess energy expenditure," *Med. Sci. Sports Exerc.*, vol. 29, pp. 144-148, 1997.

Mäntyjärvi, J., Himberg, J. and Seppänen, T., "Recognizing human motion with multiple acceleration sensors," *Proceedings IEEE Conf. Systems, Man and Cybernetics*, vol. 2, pp. 747-752, 2001.

Melanson, E.L. and Freedson, P.S., “Validity of the Computer Science and Applications, Inc. (CSA) activity monitor,” *Med. Sci. Sports Exerc*., vol. 27, pp. , 1995.

Miyazake, S., “Long-term unrestrained measurement of stride length and walking velocity utilizing a piezoelectric gyroscope,” *IEEE Trans. Biomed. Eng.*, vol. 44, pp. 753-759, 1997.

Montoye, H.J., Washburn, H.J.R., Servais, S., Ertl, A., Webster, J.G. and Nagle, F.J., “Estimation of energy expenditure by a portable accelerometer,” *Med. Sci. Sports Exerc*., vol. 15, pp. 403-407, 1983.

Morin, E.L. and Reid, S.A., “Development of a Portable Data Acquisition System for Human Performance Assessment in the Field: Phase IIa Design and Implementation of Module 2 – Physiological and Biomechanical Variables,” *DRDC Contract No. 7711-0-7632/01-TOR; Call-up no. 7632-03*, Nov. 2002.

Murgatroyd PR, Shetty PS, Prentice AM. “Techniques for the Measurement of Human Energy Expenditure: A Practical Guide”. *Int J Obesity*, 17(10):549-568, 1993.

Schutz Y, Deurenberg P. “Energy Metabolism: Overview of Recent Methods Used in Human Studies”. *Ann. Nutr Metab*, 40(4):183-193, 1996.

Schutz, Y., Weinsier, S., Terrier, P. and Durrer, D., “A new accelerometric method to assess the daily walking practice,” *Int. J. Obesity*, vol. 26, pp. 111-118, 2002.

Tong, K. and Grant, M.H., “A practical gait analysis system using gyroscopes,” *Med. Eng. Physics*, vol. 21, pp. 87-94, 1999.

Welk, G.J., Blair, S.N., Wood, K., Jones, S. and Thompson, R.W., “A comparative evalustion of three accelerometry-based physical activity monitors,” *Med. Sci. Sports Exerc*., vol. 32(9), Suppl., pp. S489-S497, 2000.

Wong, T.C., Webster, J.G., Montoye, H.J. and Washburn, R., “Portable accelerometer device for measuring human energy expenditure,” *IEEE Trans. Biomed. Eng*., vol. 28, pp. 467-471, 1981.

Development of a Portable Data Acquisition System for Human Performance Assessment in the Field - Phase IIB Validation

Appendix A - Informed Consent Form

Appendix A – Informed Consent Form

November 30th, 2001

Informed Consent Form

Evaluation of soldiers' load control patterns during a standardized mobility circuit based on load and load carriage systems

Purpose of the Study

You are being invited to participate in a research study in which Queen's Ergonomics Research Group will be assessing both battle orders and marching orders conditions. If you are among the marching orders group, you will asked to evaluate two different Load Carriage Systems (A, B) under four load conditions (10 kg, 20 kg 30 kg and a self-selected weight). If you are with the battle orders group, you will be assessing the Tactical Assault Vest (TAV). Both conditions will involve completing a mobility circuit as quickly as possible and providing the researchers with your opinions about your performance, discomfort, balance, agility and flexibility. The goal will be to determine the effect of load and pack on load control and why you like the LC system. To assist us in interpreting your answers, we will use additional scientific measures and videotape you during the sessions. The tasks you will be asked to complete have been organized into a circuit as shown in the attached photographs. The circuit and other measures will be explained later in detail.

This study is being conducted by Drs. Stevenson, Morin and Bryant of Queen's University under a research contract with the Defence and Civil Institute for Environmental Medicine (PWGSC (DCIEM) Contract W7711-0-7632). In this study we are working toward the development of a portable measurement system and a new load carriage assessment tool called a computerized biomechanical model. The reason we ask you to perform this circuit is because we want to know if the portable measurement system is sufficiently reliable and durable for field use and we want to quantify your whole body and pack motions during the tasks. We also want to ask your opinions about how the pack and load affected your mobility, agility, balance and flexibility. This information will be used to examine pack motions and design features of each pack as they relate to soldiers opinions and discomfort scores. We plan to use this information to help us develop a computer program that is sensitive to the discomfort conditions reported by soldiers. In this way, we can help develop objective standards for future load carriage systems that are based on soldiers' opinions.

Procedures during Testing

If you accept our invitation to participate in the marching orders study you will be tested on three non-consecutive days. The first test will be run at your base location. It will consist of a general briefing, completion of the Par-Q questionnaire indicating potential contraindications to exercise and a repeat of one component of your CF Fitness test, the

20m shuttle run, often called the ‘beep test”. The beep test itself can be completed in only 20 minutes with the assistance of the physical education staff, but two hours of your time was requested. The next two testing sessions will take place at Queen’s University and will require four hours to complete and you will be tired at the end of each session. You will be asked to come the back door of the Physical Education Centre on Clergy Street near University Street (ring the buzzer). Upon your arrival we will ask you to don your military fatigues, combat boots and your helmet. We will secure your personal belongings and proceed with you to Bews Gymnasium for testing. Only one soldier is tested a time.

If you accept our invitation to participate in the battle orders study you will be tested on one day. You will be asked to come the back door of the Physical Education Centre on Clergy Street near University Street (ring the buzzer). Upon your arrival we will ask you to don your military fatigues, combat boots and your helmet. We will secure your personal belongings and proceed with you to Bews Gymnasium for testing. Only one subject is tested at a time.

For all load carriage tests, we will provide you with the new Canadian Tactical Assault Vest (TAV). For the marching orders group, we will also assist you with the fitting of the two backpacks. Then we will set the strap tensions to a specific level to be consistent across all packs. We will provide you with a mock rifle and walk you through the circuit to see the layout and order of the stations. You will be given a notebook to record your data. You will be asked to remain confidential with your opinion as we do not want to bias other soldiers’ opinions. Then you will be asked to warm-up by jogging through the circuit prior to the first test.

If you come for marching orders testing, you will be asked to don either the A or B pack according to a randomized data sheet below. A research assistant will help you set the pack straps at a specific tension. Each day, you will be carrying one pack once with payloads of 0 kg, 10 kg, 20 kg or 30 kg and a self-selected load. It will require approximately 25 - 30 minutes to complete the circuit and questionnaires that will address discomfort areas, balance, mobility, flexibility and agility. Then you may doff the system and take a 15 minute break with refreshments and rest. Then you will be outfitted with the next pack load and the circuit will be repeated.

Table 1. Overview of marching orders tests (with pack weight in subscript).

Day	Additional Items	Tests and Tasks *(tasks in random order)*	Questionnaires
1	Briefing Session	Ethics, ParX, Beep Test	one
2		A_0 A_{10} A_{20} A_{30} A_{SS}	After each test item
3		B_0 B_{10} B_{20} B_{30} B_{SS}	After each test item Summary Questionnaire

If you come for battle orders testing, you will be asked to don the new Canadian Tactical Assault (TAV) vest that will be loaded with fake magazine cases to simulated standard battle orders conditions. Mounted in one of the pockets will be the portable measurement system that will take continuous data during completion of the battle orders circuit. You will complete the test circuit four times as described in Table 2 and shown in the photographs.

Instrumentation on You and in the Pack

Each subject will be carrying a portable measurement system within the pack (or TAV) as part of the weight. This portable system will be receiving the signals from strap force sensors on the pack, two accelerometers (one taped to your sternum with athletic tape and one in the pack), a heart rate monitor, skin surface and ear temperature sensors and a respiration sensor. None of this added equipment should handicap your performance, but if it does, you may remove certain equipment items and continue with the testing if desired. All of these measures are non-invasive and do not require blood or internal body measurements.

The Standardized Circuit

This standardized circuit shown in the photographs and identified in the table below has been used in 1995 and 1997 with 52 other soldiers from CFB Petawawa and CFB Kingston. No one has hurt themselves on this circuit to date. Each of these tasks will be timed and separated by marching around the gymnasium three times. The time needed to fill in questionnaires is subtracted from the total time taken and does not affect your performance time. The reason for timing the tasks is to examine any changes that may have occurred because of load weight or pack design. In all cases, perform the tasks as quickly as possible without sacrificing safety. In all cases, we want you to self-select your personal maximal pace you could sustain assuming that once you reach completion of the testing, you would be asked to conduct a Level 3 Fortification procedure. This is NOT a race. Timing each individual task will help us understand the effects of load, your body movements and pack design.

Table 2. Four station (marching orders) tasks are completed during each visit*

Balance Task Stations	Walking Balance Stations	Agility Tasks Stations	Flexibility Stations
Boulder Hop Straight Balance beam 45°balance beam	Side ramps Up/down ramps	Over/Under Fence Climb Shuttle Run	Parallel wall touch Bending about all principal axes

* Subjects coming for battle orders will also navigate under barriers (leopard crawl).

Risks and Benefits

In terms of risks during marching orders, you will be asked to carry heavy loads (0 kg, 10 kg, 20 kg and 30kg) during walking and during balancing, walking balance, agility and flexibility tasks. In terms of risks for battle orders tasks you will be moving through the circuit as quickly as possible. During either study, you will be physically tired. By the end of each period, you will have completed two hours of strenuous exercise in 30 minute blocks with 30 minutes of rest and quiet activities between each work period. Although you will have completed, on Day 1, the Par Q questionnaire that identifies exercise-related problems, you may experience cardiovascular stress and heat stress. Another potential risk is that you may develop skin abrasions, sprains or strains or trips and falls as you move quickly through the circuit. If any of these injuries occur, we will have a first aid kit available for you to access ice and first aid supplies.

To respond to any injuries that do occur, we will have an experienced athletic therapist in the building and project administrators will have a portable cell phone to ask for assistance within minutes. At least one staff member will be on hand who has certification in First Aid and Cardiopulmonary Resuscitation (CPR) to assist with any problems that may arise.

In terms of benefits you will be able to participate in the research and development of new Load Carriage systems that will eventually be worn by soldiers. The two LC systems are new designs with one being the new Canadian LC system that has not yet been issued. You will have a chance to participate in a scientific study where your opinions are valued and critical to the success of the project. You will also learn about your own body and factors affecting both physiological and biomechanical variables. You will also receive additional reimbursement for these tasks based on military pay rates.

Confidentiality

All information obtained during the course of this study is strictly confidential and will not be released in a form traceable to you. Your subjective and objective data will be kept in a locked file that is available to only the investigators, project manager and graduate student who will be performing statistics on the data. Any videotaping of the tasks will be used for one reason only: to verify timing data for the sensors. No one except the project manager, graduate student and investigators will view these tapes. As soon as the data processing and report writing are completed, these tapes will be erased. These study results will be used as anonymous data for scientific publications and presentations, and for education of students in ergonomics courses.

Freedom to Withdraw from the Study

Your participation in the study is voluntary. No one within the military will be given your results and knowledge of participation. If you specifically request it in writing, we will provide a thank you letter directed to your supervisor and copied to you acknowledging and thanking you for your participation in the study.

You are free to withdraw at any time. You will be paid for the hours committed, even if you do not complete the tasks. There will be no coercion and no military reasons to continue with the study if you choose to withdraw.

If you are dissatisfied with any aspect of the study, we encourage you to talk to a Principal Investigator, Dr. Joan Stevenson (533-6288) or (stevensj@post.queensu.ca). You may also discuss concerns with any of the following people: Major L. Bossi at DCIEM who is the military scientific authority (416-635-2197) or Dr. J. Deakin (533-6601) who is Director of the School of Physical and Health Education at Queen's University. If you have any questions about research subject's rights, you can contact Dr. A. Clark, Chair of the Research Ethics Board for the Faculty of Medicine (533-6081).

The Meaning of your Signature

By signing two copies of these Informed Consent Forms, you are acknowledging that: 1) you have been given a verbal briefing, 2) you have been given an opportunity to ask additional questions, 3) you have read this information, 4) you feel informed of the tasks and measurements requested of you, 5) you are aware of the risks and benefits of participation, 6) you will receive a copy of this form for your files, and 7) you may withdraw from the study at any time without penalty. You are also acknowledging 8) that your participation is voluntary.

Soldier's Name	Witness Name	Date
Soldier's Signature	Witness Signature	Date

Joan M. Stevenson, PhD
Professor & Principal Investigator
Load Carriage Project

DOCUMENT CONTROL DATA

(Security classification of the title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document, Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's document, or tasking agency, are entered in section 8.)

Publishing: DRDC Toronto
Performing: Ergonomics Research Group, Queen’s University, Kingston, ON, K7L 3N6
Monitoring:
Contracting: DRDC Toronto

2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)

UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification is indicated by the appropriate abbreviation (S, C, R, or U) in parenthesis at the end of the title)

DEVELOPMENT OF A PORTABLE DATA ACQUISITION SYSTEM FOR HUMAN PERFORMANCE ASSESSMENT IN THE FIELD − PHASE IIB VALIDATION (U)
MISE AU POINT D’UN SYSTÈME PORTATIF D’ACQUISITION DE DONNÉES POUR L’ÉVALUATION DE LA PERFORMANCE HUMAINE SUR LE TERRAIN PHASE IIB VALIDATION (U)

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

Evelyn Morin; Susan Reid; Joan Stevenson J. ; Tim Bryant

5. DATE OF PUBLICATION (Month and year of publication of document.)

December 2007

6a NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)

60

6b. NO. OF REFS (Total cited in document.)

21

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of document, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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8. SPONSORING ACTIVITY (The names of the department project office or laboratory sponsoring the research and development − include address.)

Sponsoring:
Tasking:

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant under which the document was written. Please specify whether project or grant.)

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

7711−0−7632/01−TOR

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document)

DRDC Toronto CR 2009−197

10b. OTHER DOCUMENT NO(s). (Any other numbers under which may be assigned this document either by the originator or by the sponsor.)

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(U) A second module, Module 2 – the Activity Assessment Module (AAM) – has been developed for the portable data acquisition system for human performance evaluation. The main purpose of the AAM is to permit the assessment of the type and intensity of work performed by a subject in the field, e.g. a soldier participating in a training exercise. This is done using two primary measures: upper body accelerations on three axes and heart rate (HR).

The AAM was evaluated in an in−door trial. Upper body accelerations and HR were monitored in subjects as they completed a standardized circuit. The subjects carried either a very light load (battle order conditions); or a light, medium or heavy load (marching order conditions). The circuit comprised seven discrete activities: walking, balance beam, boulder hop, over−under barriers and fence climb, slalom run, up−down ramp, and sidehill ramp. The results of the trial revealed the following:

- metabolic energy cost, estimated from HR, increases with increasing load carried
- metabolic energy cost, estimated from HR does not vary with the activity performed
- specific tasks can be recognized from recorded upper body accelerations
- tasks can be ordered by the magnitude of the root mean square (RMS) value of the acceleration signal, suggesting that there is a relationship between the acceleration of the body and the intensity of the work performed

The AAM performed well in comprehensive testing and promises to be a valuable tool for monitoring soldier activity.

(U) Un deuxième module – le module d’évaluation de l’activité (MEA) – a été élaboré pour le système portatif d’acquisition de données destiné à évaluer la performance humaine. L’objectif principal du MEA est d’évaluer le type et l’intensité des travaux réalisés par une personne sur le terrain, p. ex. un soldat qui participe à un exercice d’entraînement. Deux types de mesures permettent cette évaluation : ce sont la mesure de l’accélération de la partie supérieure du corps sur trois axes, et la mesure du rythme cardiaque (RC).

Le MEA a été évalué lors d’un essai à l’intérieur. L’accélération de la partie supérieure du corps et le RC ont été surveillés chez les participants qui faisaient un circuit normalisé. Les participants transportaient soit une charge très légère (attirail de guerre), ou une charge légère, moyennement lourde ou lourde (attirail de route). Le circuit comprenait sept activités distinctes : marcher, passer sur une poutre d’équilibre, ramasser un bloc, passer au dessus et en dessous d’une clôture et la grimper, courir en slalom, monter−descendre une rampe, et enfin passer sur une rampe ayant la forme d’une colline. Les résultats de l’essai ont permis de déterminer que :

- la dépense énergétique liée au métabolisme, estimée à partir du RC, augmente en fonction de la charge transportée
- la dépense énergétique liée au métabolisme, estimée à partir du RC, ne varie pas selon l’activité réalisée
- chaque tâche spécifique peut être identifiée d’après l’accélération enregistrée pour la partie supérieure du corps
- les tâches peuvent être classées en fonction de la valeur de la moyenne quadratique (MQ) du signal d’accélération, ce qui laisse supposer qu’il existe un lien entre l’accélération du corps et l’intensité du travail effectué.

Le MEA a donné des résultats intéressants lors de l’essai global et devrait être un outil valable pour l’évaluation éventuelle de l’activité des soldats.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) portable measurement system; load carriage; stress; physiological signals ; the electrodermal response; EDR; Human Performance Assessment; human performance evaluation; Portable Data Acquisition system