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EMPLOYING A TRI-AXIAL ACCELEROMETER FOR ESTIMATING ENERGY EXPENDITURE DURING SIMULATED LOAD CARRYING

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ABSTRACT

The Tritrac-R3D, a portable tri-axial accelerometer, was assessed for its ability to estimate energy expenditure during simulated load carrying activities. The Tritrac data were compared to metabolic data collected simultaneously by a MetaMax ergospirometry system while ten, healthy male subjects (aged 20.7 ±1.4 years) walked on a motorised treadmill. The subjects were measured under three conditions: no load (0%), carrying a load equivalent to 15% body mass and carrying a load equivalent to 30% body mass. When statistically compared with the MetaMax data, a significant difference of 2.105 kcal.min^{-1} was observed for the 30% load condition ($p<0.001$). This significant difference was eliminated when the data used to initialise the Tritrac was corrected to include the magnitude of the mass carried, as well as the subject's mass. Pearson Product Moment Correlations between the Tritrac and MetaMax data were calculated for each experimental condition. Correlation strength between these variables improved as the load carried increased from 0% to 30% (r=.406, .494, .818 respectively). The strongest correlation was found when all conditions were combined (r=.628) and the association was further improved when corrected Tritrac data were used (r=.857). Evidence from this study suggests that the Tritrac provides a reasonable estimate of energy expenditure gradients during load carrying activities.

Key words: Load carrying; Energy expenditure; Accelerometer.

INTRODUCTION

The assessment of habitual physical activity, whether for leisure or work purposes, has gained widespread attention from many different areas of the human movement sciences (Durnin, 1990). Unfortunately, the diversity and complexity of free-living activities make them very difficult to quantify directly, thus estimations of their frequency, duration and intensity have to be made.

Although guidelines for minimal levels of habitual physical activity must be developed for public health purposes, so too should guidelines be determined which recommend limits to continuous, sub-maximal work efforts. The majority of research and subsequent guidelines describing safe limits for heavy materials handling have focused on the relationship between the load characteristics and risk of musculo-skeletal injury, particularly to that of the back (NIOSH, 1981). When assessing continuous, sub-maximal physical activity, understanding the magnitude and rate of energy expenditure is important for several reasons. Metabolic information is necessary for the development of suitable work intensities and rest intervals (Deivanayagam & Ayoub, 1979) and provides the basis for determining maximal permissible physiological loads. This information, in conjunction with muscular strength demands, will assist in pre-employment screening and personnel selection criteria (Washburn & Safrit, 1982) and provide a better understanding of a worker's tolerance for sustained effort (Jorgensen, 1985).

There are various indirect measures that can be used to determine physiological load. The most common technique employs oxygen consumption profiles, although the cumbersome equipment associated with this method generally restricts measurement to the laboratory, often limits the mobility of the subject and otherwise alters the normal work patterns (Montoye, 1990). Heart rate records have been used to assess work intensity, although a series of subject-specific load-heart rate calibration curves generally need to be determined in the laboratory prior to *in-situ* measurement (Li *et al*., 1993). The development of motion sensors, which use directional accelerometers, has made the assessment of energy expenditure in free-moving activities more practical (Ballor *et al*., 1989). Although this methodology has been used in the quantification of physical activity for epidemiological research (Montoye *et al*., 1983), it has tremendous potential for use in ergonomic assessments. Montoye *et al*. (1996) have suggested that there is a practical, theoretical basis for estimating energy expenditure using portable accelerometers.

The component of physical activity that is most difficult to estimate is the intensity of the activity (Montoye, 1990). Thus, whatever field methodology is selected must be both a reliable and valid means of assessing rate of energy expenditure. Motion sensors have been found to be a reliable and objective measure of energy expenditure (Matthews & Freedson, 1995). Welk and Corbin (1995) found that a motion sensor followed a linear relationship with increasing heart rate. Haskell *et al*. (1993) suggested that the combination of a motion sensor and heart rate profiles improved the prediction of energy expenditure compared to heart rate alone when they assessed a variety of physical activities. However, this technique complicates data analysis and could become less reliable when factors, other than activity intensity, affect heart rate (Green *et al*., 1986, McArdle *et al*., 1991).

When examining a work situation over an extended period (e.g., an eight-hour shift) a person will often perform a number of different tasks. These tasks will consist of both static and dynamic efforts, and often a combination of both, such as holding and carrying (Sanchez *et al*., 1979). Although tri-axial accelerometers have been validated with activities such as walking (Bouten *et al*., 1994) and free play in children (Welk & Corbin, 1995), for technological reasons these devices may not accurately record static activity, such as added weight from carrying or lifting an object, due to the lack of body motion associated with these activities. Bouten *et al*. (1994) acknowledged the obvious shortcoming of motion sensors to be the underestimation of energy expenditure of activities that have static components. They indicated that this might not be a serious limitation in the technology, as the amount of static exercise is minimal in normal daily physical activities. This assumption, however, may need to be addressed when employing motion sensors in assessing manual materials handling occupations, where lifting and carrying activities are common to job descriptions. If tri-axial accelerometers are to be successfully incorporated into the evaluation of free-living activities, these devices will have to be validated under mixed-activity settings.

The purpose this study was to determine whether a commercially available tri-axial accelerometer can be used to quantify metabolic expenditure during load carrying activities often typical of activities of daily living.

METHOD

Subjects

Ten male volunteers from the university student population agreed to participate in this study. Table 1 contains mean descriptive measures of the experimental subjects and condition characteristics. No subject reported a current illness or a history of shoulder, elbow, wrist or back pain. No subject reported a current or past history of smoking. While subjects were student volunteers, all were physically active and could be considered suitable surrogates for an industrial work force. The protocol was approved by the Rhodes University Human Kinetics and Ergonomics Ethics Committee and informed written consent was obtained from all subjects prior to participation.

TABLE 1. **SUBJECT AND CONDITION CHARACTERISTICS**

	Age (Years)	**Stature (m)**	**Mass (kg)**	**Walking Speed (km/hr)**	**15% Load (kg)**	**30% Load (kg)**
mean	20.67	1.82	78.95	4.26	11.83	23.68
sd	1.41	0.07	9.34	0.15	1.39	2.81
max	24.00	1.93	91.56	4.51	13.65	27.50
min	20.00	1.70	66.74	3.99	10.01	20.02
cv	6.84	3.57	11.84	3.54	11.75	11.87

Apparatus

Energy expenditure estimates collected by two methods were compared over three conditions of load carrying. The first method employed a Tritrac R3D (Hemokinetics, Inc. Madison, WI, USA) to estimate energy expenditure in kilocalories per minute ($kcal.min^{-1}$). This is a small, lightweight tri-axial accelerometer (.227 kg) which is secured snugly around the waist of the subject (see figure 1). Prior to the beginning of the experimental protocol, the subject's mass, stature, age and sex were entered into the device via a microcomputer interface. The reader should refer to Matthews and Freedson (1995) for a description of the operation of the Tritrac. The data were stored in 1-minute intervals within the unit for later uploading to the microcomputer.

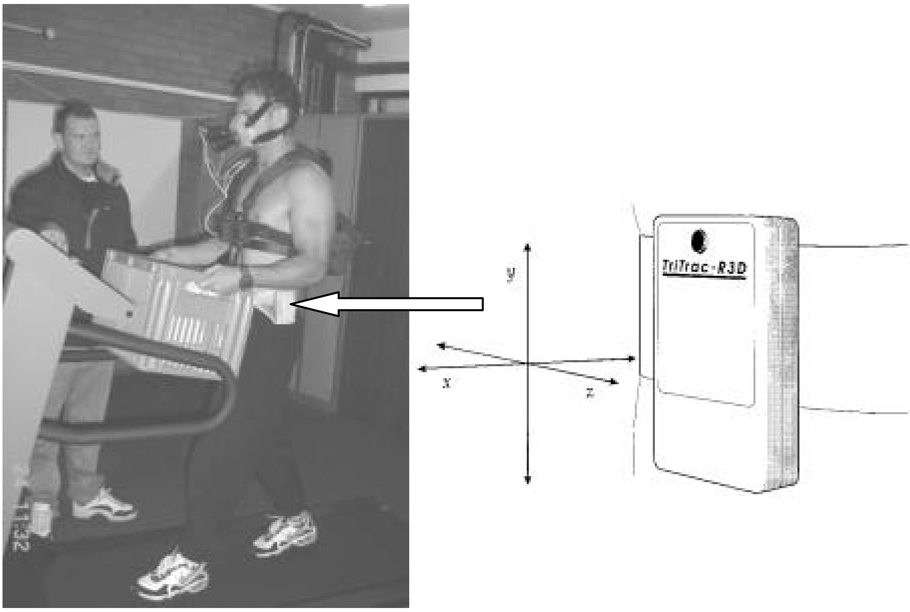


FIGURE 1. **EXPERIMENTAL SET-UP INCLUDING ILLUSTRATION OF TRITRAC UNIT**

The second method used to estimate energy expenditure employed the MetaMax Ergospirometry System (CORTEX Biophysik GmbH, Leipzig, Germany) which measures oxygen uptake and ventilation continuously at 10-second intervals. Data were stored in real-time and saved for later analysis. Both the Tritrac and the MetaMax are relatively unobtrusive to the subject's movement and should not have limited their ability to perform the experimental protocol. Polar heart rate monitors (Polar Electro Oy, Kempele, Finland) monitored heart rates in 5-second intervals.

Experimental design

Subjects were required to walk on a motorised treadmill at a speed of 0.65 statures.s^{-1} for 12 minutes under three conditions, which were presented to each subject in a randomised order. The three conditions included walking without load, with a load equivalent to 15% of the subject's mass and with a load equivalent to 30% of the subject's mass. The loads were carried with the hands, in front of the subject's body, in a .035 m^3 box which had comfortable handles on its sides.

Following each condition, the subject sat down to recover. The next condition did not commence until the subject had recovered to initial resting heart rate and oxygen consumption levels. This was done to minimise the effects due to fatigue.

Statistical analyses

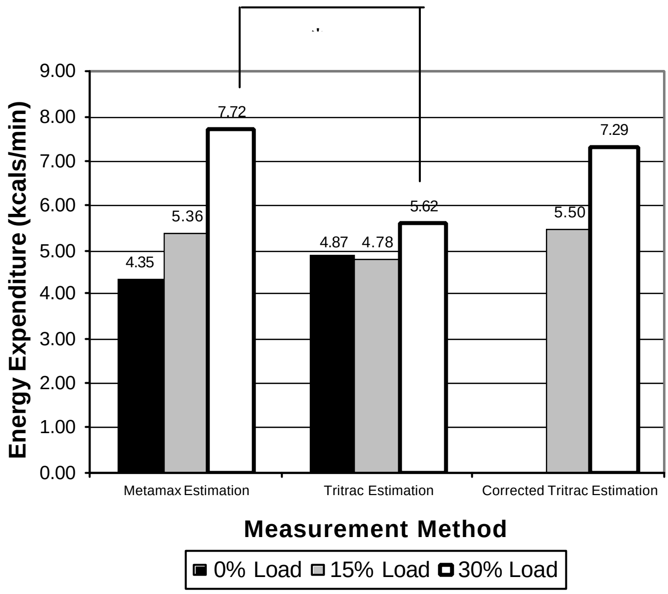
Although data were recorded over 12 minutes for each condition, minutes four through eight were selected for analysis. The first three minutes were excluded from the analysis in order to ensure the subject had achieved steady-state metabolism. The last four minutes of the trial were excluded to ensure that fatigue did not cause changes in the metabolic profiles or the mechanics of walking with a load. Mean values were calculated for each dependent variable across the 5-minute interval.

In order to compare the MetaMax metabolic data with the Tritrac data, the oxygen consumption profiles, in $l.min^{-1}$, were converted into $kcals.min^{-1}$. This was done by assuming a mixed diet metabolism where 4.825 kilocalories were required to burn one litre of oxygen (McArdle *et al*., 1991).

A paired t-test was employed to determine the differences between the estimated energy expenditure from the Tritrac and MetaMax systems for each walking condition. A repeated measures analysis of variance was used to assess differences in each experimental variable across load conditions. Finally, a Pearson Product Moment correlation was used to assess the relationship of the Tritrac data against the oxygen consumption data for each load condition.

RESULTS

Figure 2 depicts the energy expenditure ($kcal.min^{-1}$) data derived from the MetaMax and the Tritrac. Employing a paired student t-test, a significant difference between the MetaMax and Tritrac values was observed only for the 30% load condition ($p<0.05$). In the initialisation process of the Tritrac, only the subject's mass was entered. As a post hoc procedure, the Tritrac data were mathematically corrected to include the mass carried by each subject for the 15% and 30% mass load conditions. This was done by dividing the Tritrac data for each minute by the subject's mass to determine a relative energy expenditure, then multiplying this value by the subject's mass plus load, to give a load corrected value in $kcal.min^{-1}$. These data are also included in figure 2. The significant difference observed in the 30% mass condition is eliminated by this correction procedure.



* - denotes significant difference at p>.05

FIGURE 2. **COMPARISON OF METAMAX AND TRITRAC ENERGY EXPENDITURES (KCAL.MIN^{-1}) ACROSS CONDITIONS**

To determine if the instruments could distinguish between experimental conditions, a one-way analysis of variance (ANOVA) was conducted between the kilocalorie expenditure for both the MetaMax and the Tritrac as well as the average heart rate in beats.min^{-1} (see table 2). Results revealed that there were significant differences between the three experimental conditions for both the heart rate and MetaMax data. Post hoc analysis (Scheffe-t) revealed that each condition was significantly different from each other. Although the ANOVA revealed a significant difference in the Tritrac data across all three conditions, the post hoc analysis indicated that the difference in the 0 and 15% load was not significant. Table 3 contains the summary heart rate values obtained for each condition.

TABLE 2. **BETWEEN TREATMENT REPEATED MEASURES ANALYSIS OF VARIANCE**

Variable	**F-score**	**p-value**
Heart Rate(beats/min)	0.848	0.5748
MetaMax (Kcal/min)	0.6	0.7659
Tritrac (Kcal/min)	11.836	0.0007
Corrected Tritrac (Kcal/min)	48.95	0.0007

TABLE 3. **MEAN (AND STANDARD DEVIATION) HEART RATE VALUES ACROSS CONDITIONS**

	0%	**15% Load**	**30% Load**
Heart Rate (beats.min-1)	90.4 (10.7)	103.3 (10.7)	134.7 (11.0)

Table 4 contains the Pearson Product Moment Correlations between the experimental variables contained in figure 2. Also included in table 4 are the correlation coefficients from the data of the three conditions combined.

TABLE 4. **CORRELATION COEFFICIENTS BETWEEN METAMAX AND TRITRAC ESTIMATIONS**

Condition		r
0% Load	Metamax vs Tritrac	0.406
15% Load	Metamax vs Tritrac	0.494
	Metamax vs Corrected Tritrac	0.494
30% Load	Metamax vs Tritrac	0.818*
	Metamax vs Corrected Tritrac	0.817*
Combined	Metamax vs Tritrac	0.628*
	Metamax vs Corrected Tritrac	0.857*

* - denotes statistical significance at $p<0.05$

DISCUSSION

This study examined the ability of the Tritrac monitor to estimate energy expenditure in comparison to the MetaMax metabolic system during a standardised load-carrying protocol. This research attempts to answer two specific questions: can the Tritrac estimate energy expenditure under load carrying conditions and can the Tritrac be used to assess energy expenditure for activites of daily living that require load manipulation? This research is somewhat novel for studies which employ motion sensors, as it attempts to simulate a free-living activity, in which mixed muscle activations, including dynamic lower body movement (i.e. walking) and quasi-static upper body exertions (i.e., carrying) occur. Previous protocols that have assessed the validity of motion sensors have used changes in walking/running speed or grade as a means of changing the workload experienced by the subject. In a series of standardised laboratory tests, Haskell *et al*. (1993) indicated that motion sensors provided unreliable energy expenditure estimates in activities where the intensity changes were due to increases in resistance rather than increases in speed of movement. Similar findings were observed in this study; as load increased the absolute magnitude differences compared to the Metamax data increased, unless the 'correction' procedure was employed.

Ballor *et al*. (1989) speculated that accelerometers might underpredict activities that involve lifting because there are minimal vertical accelerations of the body's centre of mass. However, carrying activities will affect the vertical and horizontal accelerations of the body's centre to a greater extent than lifting and thus should be more easily measured by a triaxial motion sensor. Figure 2 revealed that there were no significant differences in the energy cost estimated by the Tritrac compared to the metabolic analysis for the 0 and 15% load conditions. Although there was a significant difference in the 30% load condition, this difference was minimised when the Tritrac estimate was corrected to include the carried mass.

A load of 30% body mass carried for an extended period of time may become quite taxing to an individual. Zhu and Zhang (1990) reported that average heart rates below 115 beats.min^{-1} could be tolerated over a full workday. In the 0% and 15% body mass load, the heart rates fell below these upper limits (see table 3), while the 30% body mass load appeared to be a condition which could not be endured over an extended period without adequate rest periods. Anecdotal evidence suggested that during this condition, the subjects in this experiment tended to place the load against the pelvis and thigh and extend the back in order to support the load. From a mechanical perspective, this would decrease the amount of trunk movement and thus whole-body acceleration, accounting for the lowered Tritrac estimation, but physiologically this compensatory action would increase the energy expenditure due to the increased activity in the back extension and hip flexion musculature due to the higher inertial properties of the load.

In a summary of validation studies done on the Caltrac, a similar motion sensor to the Tritrac but which only measures acceleration in the vertical direction, Montoye *et al*. (1996) found that the Caltrac consistently overestimated the energy expenditure during treadmill walking and running. It is interesting to note, that the Tritrac tended to underestimate the energy expenditure in the load carrying conditions (see figure 2), although these differences were generally not significant. These findings were similar to a study that compared metabolic measures to the Tritrac during 2-day backpacking excursions (DeVoe & Gotshall, 1998) in which the Tritrac consistently underpredicted the metabolic energy expenditure.

Table 2 revealed that both mean heart rate and oxygen consumption increased significantly with increasing load condition. This finding was not unexpected, considering the progressive increase in resistance from condition to condition. From this table, it may appear that the differences in Tritrac values would be significantly different across all conditions. However, the Tritrac recorded no significant difference between the energy expenditure estimated for the 0 and 15% load. This lack of significant difference is difficult to explain, but may be because the load increase from the free-walking condition was not sufficient enough to cause a measurable change in the movement of the body's centre of mass. Pierrynowski *et al*. (1981) found similar results in load carrying with a backpack. The rate of increase of the mechanical energy with increasing load was less than simultaneously measured physiological cost. Similar to this study, they found that the mechanical cost at the lighter load conditions even decreased with increasing load.

An important focus of this study was to assess the relationship, and subsequently the utility of the Tritrac device to predict energy expenditure. Table 4 reveals there is a poor degree of association between the Tritrac and the MetaMax data for the 0% and 15% load conditions, although there were no significant differences in magnitude between the Tritrac and MetaMax data for the 0% and 15% loads. From a statistical perspective, both the corrected and uncorrected Tritrac data predict the metabolic data more reliably as the load carried increases. There exists a significant correlation between the Tritrac and metabolic data for the 30% load. When all three experimental conditions are combined, the strength of the correlation increases considerably (see table 4).

The lack of significant correlations between the Tritrac and Metamax values at lighter loads while no significant differences in the absolute data are observed may seem contradictory. However, this might reflect the ability of a subject to maintain a natural gait pattern at lighter loads which would greatly effect the inter-subject variability in the acceleration profiles in all directions. Prediction of metabolic expenditure by the Tritrac is determined by a regression equation which uses the acceleration vectors as input variables. As the load is increased, upper body musculature is likely more active to stabilise the body and thus influence the movement of the upper body. This might tend to make acceleration profiles more consistent between subjects and would improve the degree of association in the prediction of metabolic costs, while not necessarily improving the prediction.

Masse *et al.* (1999) suggested that the Tritrac was a useful tool for detecting bouts of moderate-intensity physical activity in a field setting. While these authors examined faster walking speeds than this study, their subjects were not required to carry loads. These results further supports the use of the Tritrac as an objective measure of mixed daily or occupational activities measured over an extended period of time particularly if light or moderate loads are being manipulated by the person.

CONCLUSIONS

Findings should be considered in light of the small sample size employed in the study even though there is a reasonable degree of assocation between the two measurement techniques. While a study with a larger sample size may better validate the robustness of the Tritrac monitor to estimate energy expenditure, the following statements are justified.

Similar to the findings of other studies that have assessed the reliability of motion sensors, the results from this study suggest that a reasonable, relatively inexpensive estimate of energy expenditure for light, load carrying activities (i.e., below 30% body mass) may be obtained from the Tritrac. Therefore, researchers may be able to use the Tritrac to assess energy expenditure for combined static and dynamic, free-living leisure or occupational activities. The Tritrac estimations become more valid when the subject mass-plus-load is considered at the time of instrument initialisation or when corrected in a post hoc fashion prior to data analysis. This correction process becomes problematic, however, if the Tritrac unit is used to monitor energy expenditure over an extended period where the nature of the activities periodically changes and are unmonitored by the investigator.

REFERENCES

BALLOR, D.L.; BURKE, L.M.; KNUDSON, D.V.; OLSON, J.R. & MONTOYE, H.J. (1989). Comparison of three methods of estimating energy expenditure: Caltrac, heart rate, and video analysis. *Research Quarterly for Exercise and Sport*, 60(4): 362-368.

BOUTEN, C.V.; WESTERTERP, K.R.; VERDUIN, M. & JANSSEN, J.D. (1994). Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Medicine and Science in Sports and Exercise,* 26: 1516-1523.

DEIVANAYAGAM, S. & AYOUB, M.M. (1979). Prediction of endurance time for alternating workload tasks. *Ergonomics*, 22(3): 279-290.

DEVOE, D. & GOTSHALL, R.W. (1998). Validity of the Tritrac-R3D accelerometer during backpacking: A case study. *Journal of Human Movement Studies*, 34: 271-281.

DURNIN, J.V.G.A. (1990). Assessment of physical activity during leisure and work. In C. Bouchard; R.J. Shephard; T. Stephens; J.R. Sutton & B.D. McPherson (Eds.), *Exercise, fitness, and health: A consensus of current knowledge* (63-70). Champaign, IL: Human Kinetics.

GREEN, M.S.; LUZ, Y.; JUCHA, E.; COCOS, M. & ROSENBERG, N. (1986). Factors affecting ambulatory heart rate in industrial workers. *Ergonomics,* 29(8): 1017-1027.

HASKELL, W.L.; YEE, M.C.; EVANS, A. & IRBY, P.J. (1993). Simultaneous measurement of heart rate and body motion to quantitate physical activity. *Medicine and Science in Sports and Exercise*, 25(1): 109-115.

JORGENSEN, K. (1985). Permissible loads based on energy expenditure measurements. *Ergonomics,* 28(1): 365-369.

LI, R.; DEURENBERG, P. & HAUTVAST, G.A.J. (1993). A critical evaluation of heart rate monitoring to assess energy expenditure in individuals. *American Journal of Clinical Nutrition,* 58: 602-607.

MASSE, L.C.; FULTON, J.E.; WATSON, K.L.; HEESCH, K.C.; KOHL III H.W.; BLAIR, S.N. & TORTOLERO, S.R. (1999). Detecting bouts of physical activity in a field setting. *Research Quarterly for Exercise and Sport*, 70: 212-219.

MATTHEWS, C.E. & FREEDSON, P.S. (1995). Field trial of a three-dimensional activity monitor: Comparison with self report. *Medicine and Science in Sports and Exercise,* 27(7): 1071-1078.

MCARDLE, W.D.; KATCH, F.I. & KATCH, V.L. (1991). *Exercise physiology: Energy, nutrition, and human performance* (3rd ed). Philadelphia, PA: Lea & Febiger.

MONTOYE, H.J. (1990). Discussion: Assessment of physical activity during work and leisure. In C. Bouchard; R.J. Shephard; T. Stephens; J.R. Sutton & B.D. McPherson (Eds.), *Exercise, fitness, and health: A consensus of current knowledge* (71-74). Champaign, IL: Human Kinetics.

MONTOYE, H.J.; KEMPER, H.C.G.; SARIS, W.H.M. & WASHBURN, R.A. (1996). *Measuring physical activity and energy expenditure.* Champaign, IL: Human Kinetics.

MONTOYE, H.J.; WASHBURN, R.; SERVAIS, S.; ERTL, A.; WEBSTER, J.G. & NAGLE, F.J. (1983). Estimation of energy expenditure by a portable accelerometer. *Medicine and Science in Sports and Exercise,* 15: 403-407.

NIOSH (1981). *Work practices guide for manual lifting*. DHHS (NIOSH) Publication no. 81-122.

PIERRYNOWSKI, M.R.; NORMAN, R.W. & WINTER, D.A. (1981). Mechanical energy analyses of the human during load carriage on a treadmill. *Ergonomics*, 24(1): 1-14.

SANCHEZ, J.; MONOD, H. & CHABAUD, F. (1979). Effects of dynamic, static and combined work on heart rate and oxygen consumption. *Ergonomics,* 22(8): 935-943.

WASHBURN, R.A. & SAFRIT, M.J. (1982). Physical performance tests in job selection: A model for empirical validation. *Research Quarterly for Exercise and Sport,* 53(3): 267-270.

WELK, G.J. & CORBIN, C.B. (1995). The validity of the Tritrac-R3D Activity Monitor for the assessment of physical activity in children. *Research Quarterly for Exercise and Sport,* 66(3): 202-209.

ZHU, Z. & ZHANG, Z. (1990). Maximum acceptable repetitive lifting workload by Chinese subjects. *Ergonomics*, 33: 875-884.

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