

Oxygen consumption prediction models for individual and combination materials handling tasks

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An experiment was conducted to develop models to predict oxygen consumption of males and females engaged in common materials handling tasks including lifting, lowering, pushing, pulling, (de)palletising and combination tasks involving lifting or lowering a box and carrying it a set distance and lifting or lowering it to the destination. Nineteen male and 19 female subjects participated in the study. A psychophysical approach was used to set load limits for individual subjects for the oxygen consumption protocol. The 8398 oxygen consumption values collected were entered into the initial regression analyses and 168 potential outliers were removed before the final models were run. In addition to relevant task variables, body weight was a significant predictor variable in all models. The r^2 values for the final models ranged from 0.54 to 0.82 and the root mean square errors ranged from 90.2 ml to 294.8 ml.

Keywords: materials handling; work physiology; oxygen consumption

1. Introduction

Ergonomic trends suggest that designing jobs within the physiological capacity of a workforce is becoming increasingly important. Dempsey (2003) reported a survey of lifting and lowering task parameters collected between 1997 and 2000 and compared the results to a similar survey of parameters collected between 1981 and 1993 (Ciriello and Snook 1999). A trend of decreasing loads and increasing frequencies was present across this time frame with an approximate halving of loads and doubling of frequency over the period. Although there are several possible explanations, such as the effect of ergonomic recommendations to reduce load, or the increased use of mechanisation that may increase frequency, the data indicate the importance of accommodating the physiological capacities of workers. Karlqvist *et al.* (2003) corroborated this by their investigation of the relationship between aerobic capacity and job demands. Job demands in excess of one-third of aerobic capacity were found for 27% of the sample of 94 males and 22% of the sample of 94 females.

A demographic change influencing accommodation of the physiological capacity of the workforce is the ageing of working populations around the globe (Commonwealth of Australia 2001, Ilmarinen 2001, National Institute for Occupational Safety and Health 2004). Combined with the increasing percentage of females in the workforce

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(National Institute for Occupational Safety and Health 2004), accommodating a majority of the workforce will require designing jobs to a lower energy expenditure requirement. This is due to the well-known decrease of aerobic power with age (the peak is generally before age 30) and the lower mean aerobic power of females compared to males (e.g. Ilmarinen 1992, Jackson *et al.* 1995, 1996, Faber *et al.* 2006).

The physiological approach is one of the three main approaches to analysing and designing manual materials handling (MMH) tasks. In contrast with the biomechanical approach that is most appropriate for high load and lower frequency tasks, the physiological approach is appropriate for lighter loads with high frequency rates. The psychophysical approach is most appropriate for tasks with moderate frequencies. Kim (1990) and Ayoub (1992) recommended that the lowest load or force from among the values provided by the three approaches be used as the design criterion.

In ergonomics, energy expenditure limits are often expressed in terms of rate of oxygen consumption per min ($\dot{V}O_2$). A limit of 1 litre of oxygen per min (approximately 5 kcal per min) is a common design criterion. Due to the cost and difficulty of measuring oxygen consumption in the workplace, there have been various approaches investigated in the laboratory as surrogates for direct measurement (Malhotra *et al.* 1963, Ramanathan 1964, Sharkey *et al.* 1966, Andrews 1967, Datta and Ramanathan 1969, Bernard *et al.* 1979). For MMH tasks, models that predict $\dot{V}O_2$ from personal and task variables have been used to assess physiological demands. This approach can be traced back at least to early work by Frederik (1959). Several investigators have developed such models (Garg *et al.* 1978, Taboun and Dutta 1989).

One advantage of the Garg *et al.* (1978) models is that they are robust with regard to types of tasks included and can be used to estimate the energy expenditure for a wide variety of jobs. This is achieved by assuming that the energy expenditure of a job is the sum of the energy expenditures of the tasks and task elements that comprise the job. However, the additivity assumption can lead to high errors. Andrews (1966) found errors of 20% or more for four configurations of task combinations, although smaller or non-significant differences were found for some configurations. Genaidy *et al.* (1985) reported absolute errors associated with the additivity assumption for different combinations of lifting and lowering tasks to be from 19–45%. Taboun and Dutta (1989) investigated this assumption for a lift and carry task and found that the absolute errors ranged from underestimates of 25% to overestimates of 60%.

For a lift-carry-lower task, Ciriello *et al.* (1993) found that the lift component had the lowest psychophysical value and suggested this task was the limiting task when using the psychophysical approach. However, they found that combination tasks had $\dot{V}O_2$ values that were 30% higher than that for the low lift component, suggesting that the physiological approach should be used to set limits for combination tasks rather than psychophysics.

In a recent study of certified professional ergonomists (Dempsey *et al.* 2005), 43.5% of respondents indicated prior use of energy expenditure prediction models. In spite of this rather widespread use, several of the $\dot{V}O_2$ prediction models were developed with limited samples of fairly young subjects (Garg *et al.* 1978, Taboun and Dutta 1989). The most widely used models (Garg *et al.* 1978) may not be generalisable to more diverse populations with different anthropometrics and prediction errors of almost 28% have been reported (e.g. Kim 1990). Thus, there is a need for models developed from a more diverse and larger sample than those studied previously.

The purpose of the study reported here was to develop a set of regression models to predict $\dot{V}O_2$ during performance of individual (lift, lower, push, pull, carry) and combination (lift-carry-lower, palletising, depalletising) materials handling tasks from a

representative sample of experienced male and female materials handlers. The combination tasks chosen are commonly encountered (Dempsey 2003) and developing models specific to the performance of the tasks as a unit rather than estimating from adding the costs of the individual lift, carry and lower components alleviates the additivity problem discussed earlier.

2. Methods

2.1. Subjects

A total of 19 male and 19 female subjects with industrial materials handling experience were recruited with a local newspaper advertisement. Table 1 gives the demographics of the subject sample that participated in the $\dot{V}O_2$ protocol. Recruitment was limited to subjects between 18 and 65 years of age. Individuals who responded to the advertisement were given a group presentation describing the details of the experiment including tasks, hours, etc. and were asked to complete medical screening forms. The compensation for the first half of subjects run was US\$12 per hour with a \$300 completion bonus at the end of the 10-week protocol. The hourly wage increased to \$15 for the second half to accommodate increases in local wages with the same completion bonus. After a tour of the experimental set-up in the work physiology laboratory, interested individuals completed application forms and signed the informed consent approved by the Liberty Mutual Research Institute for Safety Institutional Review Board.

2.1.1. Subject screening

Potential subjects without a history of low-back problems, cardiovascular or respiratory disease or other acute or chronic musculoskeletal issues who were interested in the study were invited to have a medical screening by a physician's assistant. Of those who passed the medical exam, up to six subjects per group were invited to undertake the study. The study had two phases: a 4 week psychophysical protocol; and a 6 week phase during which the $\dot{V}O_2$ measurements were taken. The psychophysical methodology (Snook and Ciriello 1991) described later was used to set individual subject limits for weights for lift, lower and carry tasks and forces for push and pull tasks. This was done to allow $\dot{V}O_2$ data to be collected across the widest range possible while not exposing subjects to weights or forces beyond what they were willing to handle or exert, respectively.

2.2. Psychophysical protocol

2.2.1. Apparatus

Lifting and lowering tasks were performed on pneumatically activated shelves that have been used in numerous studies in this laboratory (e.g. Ciriello *et al.* 1993, Ciriello 2007).

Table 1. Mean (SD) of subject demographics.

Gender	n	Age (years)	Height (cm)	Weight (kg)	Shoulder height (cm)	Elbow height (cm)	Knuckle height (cm)
Female	19	38.7 (9.6)	164.6 (6.6)	72.4 (14.4)	134.8 (6.2)	105.1 (4.4)	73.5 (3.8)
Male	19	40.3 (11.4)	177.5 (5.6)	92.3 (15.6)	148.1 (5.3)	113.7 (4.8)	80.0 (4.5)

Once the subject removed the box from the shelf at the lift origin, the shelf automatically moved to the destination location. When the box was placed on the shelf at the destination, the shelf would return the box to the origin location for the next lift or lower. This allowed the subject to do the same lift or lower continually while using the same box. The box was an industrial tote 33.4 cm wide, 56.2 cm long and 16.0 cm deep. This size tote has been used as a criterion box in this laboratory (Snook and Ciriello 1991). Subjects could add or remove steel shot as required by the psychophysical procedure.

The pushing and pulling tasks were performed using both a specially instrumented treadmill with an adjustable magnetic particle break and a pushcart with adjustable weight. The treadmill was powered by subjects pushing on an instrumented bar while walking. Increasing the electric current to the magnetic particle break would increase the force required to do this. A control knob within reach of the subjects or one at the experimenter's workstation could adjust the current. For the pushcart, water was pumped into or out of the cart to adjust force requirements (see Ciriello *et al.* 1999 for more details).

2.2.2. Training and psychophysical procedures

Depending on availability, up to six subjects started the initial psychophysical protocol. All subjects dressed in hospital scrubs to control for differences in personal clothing. They were provided with new neoprene-soled shoes to ensure consistent coefficients of friction for pushing and pulling tasks. The subjects began with a 3-d training programme that progressively increased their workload and allowed them to gradually become familiar with the psychophysical procedure, tasks to be performed and apparatus. The training programme progressed as follows: on day 1, subjects performed six 10-min tasks; on day 2, six 20-min tasks; on day 3, six 30-min tasks. The psychophysical data collection began on day 4 and over the next four visits subjects completed 20 tasks – five 40-min tasks separated by 10-min breaks. The 8th day was reserved for re-running up to five tasks that had the highest variation between trials or that had been missed due to equipment failure, tardiness, etc. For the duration of experimentation, subjects typically worked two 4-h shifts per week.

Subjects were instructed to adjust the amount of weight or force until it represented the maximum they could handle for 8 h without 'straining themselves or without becoming unusually tired, weakened, overheated or out of breath'. During lifting, lowering and carrying tasks, subjects varied the weight of the tote boxes by adding or subtracting steel shot. In an attempt to minimise visual cues, the boxes contained false bottoms that could hold up to 18 kg for men and 11 kg for women. Subjects were aware of the false bottoms but never knew the weight that was in the false bottom. The weights in the false bottom were randomly varied. For each psychophysical estimation, subjects completed two trials, with alternately high and low initial loads or forces. The average of the two trials was used as the datum.

2.3. Oxygen consumption protocol

2.3.1. Apparatus

The metabolic measurements were conducted with a Cosmed K4b² portable metabolic measurement system (Cosmed USA Inc., Chicago, IL, USA) and a Metabolic Measurement Cart (SensorMedics 2900; SensorMedics Corp., Yorba Linda, CA, USA).

Tasks were performed using the same pneumatically activated shelves, treadmill and pushcart described earlier. The particle break and cart weight were adjusted to modify the amount of sustained force required while pushing or pulling on the treadmill and pushcart, respectively. For the (de)palletising tasks, a simulated (de)palletising area was set up with two pallets (1.2 m $\times$ 1.2 m $\times$ 0.14 m) both 1 m from a section of roller conveyor that was 0.75 m high. At any given time, two subjects would work, one palletising and one depalletising.

Carrying tasks were performed between a pair of open shelves that allowed access from both sides. The shelves were set either 2.1 m, 4.3 m or 8.5 m apart and subjects performed carries in pairs, with one subject returning the box for the subject whose metabolic rate was being measured. For males and females, the lowest shelf (floor) was set to 14 cm. The centre shelf (knuckle) was set to 76 cm for females and 81 cm for males, while the highest shelf (shoulder) was set to 137 cm for females and 145 cm for males.

Cardboard boxes without handles were used for the $\dot{V}O_2$ part of the study since they are typically what workers handle in the workplace. The larger measured 0.5 m wide $\times$ 0.5 m long $\times$ 0.3 m deep and was used for all non push/pull tasks. A smaller box, which was 0.3 m³, was also used on the lifting, lowering and (de)palletising tasks. The tote box and small and large cardboard boxes including foam inserts are shown in Figure 1.

The weights of these boxes were fixed; 2.5, 5, 10 and 15 kg for women; and 5, 10, 15, 20 and 25 kg for men. Individual subjects were only required to handle boxes up to the weight suggested by their psychophysical limit on a particular task. The weights were changed by adding or subtracting steel bars into the foam inserts. The bars were placed in symmetric patterns front to back and side to side so that the load would be as evenly distributed as possible.

2.3.2. Oxygen consumption procedures

Oxygen measurements were taken during 12 4-h shifts spread over the remaining 6 weeks. The task parameters across all tasks are listed in Appendix 1. Each group of subjects performed these tasks at two pre-determined frequencies. The frequencies were changed for each group to provide a wide spread of frequencies across the tasks. Some subjects performed tasks at three frequencies if their psychophysical limit did not permit them to

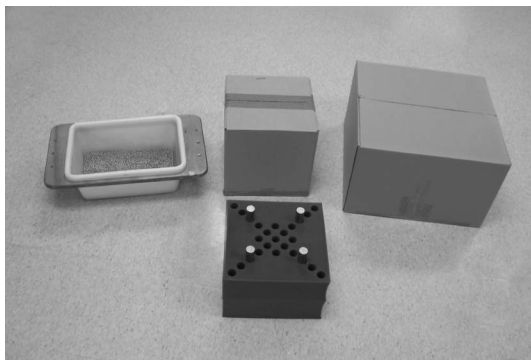


Figure 1. The tote box and small and large cardboard boxes including foams inserts used in the experiment.

complete many loads. Groups of up to four subjects could be run at a given time for the $\dot{V}O_2$ protocol.

Before data collection began, subjects were outfitted with the oxygen measurement equipment. For the Cosmed, this consisted of the oxygen measurement portable unit and battery pack attached to the subject via harness and a facemask with one-way valves and a turbine. All expired air was sent through the turbine to measure volume and the portable unit analysed a sample of each expired breath for oxygen and carbon dioxide content.

The SensorMedics system involved the subjects wearing a facemask outfitted with a one-way valve. Unlike the Cosmed, expired air was directed through a collection hose to the metabolic cart, which performed metabolic measurements. Both metabolic carts were calibrated using commercially available precision gases prior to and after each session. The pneumotach was calibrated using a 3 litre syringe to ensure accuracy of the expired ventilation volume measurements.

Subjects would begin work at the lowest frequency with the lightest load for a particular task. Frequency was controlled via metronome as in the psychophysical experiment. After reaching a stable metabolic rate (within 3 to 4 min period of performing the activity) the subject's $\dot{V}O_2$ was measured for 1 min. Readings were taken every 20 s and the average of three readings were used as the datum. After the initial oxygen measurement was taken, the load was increased and, once the subject reached steady state with the new load, another reading (or set of readings by the Cosmed) was taken. When the maximum load for any particular task, as determined by that subject's results from the psychophysical part of the study, was reached, experimentation was stopped and subjects were given a short rest. The load was changed back to the lightest, the frequency increased and the task re-started. This continued until all the readings were taken for any particular task (or until the subject had been working for 40 min). Work was then stopped and the subjects were given a 10-min rest.

2.4. Regression modelling

$\dot{V}O_2$ values, task parameters and subject weights were entered into a spreadsheet for statistical analysis. All statistical analyses were performed with SAS 9.1[®] for Windows (SAS Institute, Cary, NC, USA). Regression models were developed separately for males and females and for each type of task. Variables initially entered into the models included: (1) push/pull models – body weight, sustained horizontal force, a dummy variable for treadmill vs. pushcart, frequency, and distance; (2) (de)palletising models – body weight, a dummy variable for palletising vs. de-palletising, a dummy variable for box size, frequency and box weight; (3) combination tasks – body weight, carry distance, frequency and box weight; (4) lift/lower models – body weight, box size, frequency and load weight.

In order to check for outliers, studentised residual values with an absolute value greater than 2.0 obtained with the RSTUDENT option were examined (SAS Institute, Inc. 1989). The $\dot{V}O_2$ values for potential outliers based on studentised residuals were examined in the context of the other data collected for that subject and type of task to determine if there were possible equipment problems, such as a leaking mask, or other potential problems with the observation. Outliers were only removed if there was reasonable evidence that the observation may have been in error, such as when an observation was lower than expected relative to that subject's other observations for similar conditions. While the ± 2.0 value for studentised residuals was used as a guide, it was never considered sufficient on its own. Two of the authors (P.G.D., N.V.O.) considered the outliers until concurrence was reached.

Residual plots were visually examined and partial regression plots were examined to assess potential non-linear effects for individual predictor variables. For pushing, pulling and carrying tasks, a common trend of heteroscedasticity was noted with larger residuals at higher $\dot{V}O_2$ values. The partial regression plots for frequency and push/pull/carry distances also indicated possible issues, so an interaction term between frequency and distance was added to each of these models. This resulted in the distance term becoming insignificant in the models as the interaction term actually represents distance per min. The models improved with this change and the heteroscedasticity issues and problems noted with partial regression plots resolved. In a few cases, frequency also dropped out of the models.

3. Results

The 8398 observations were entered into the initial statistical analyses. There were 598 observations for palletising and depalletising, 1132 for pushing and pulling, 1761 for lifting and lowering and 4907 for the combination tasks involving a carry. Males had 4705 observations and females had 3693, the difference largely due to the higher psychophysical capacity of males, hence a wider range of loads handled.

As part of the residual diagnostics, 168 observations (2%) were removed. The regression models were re-run without these observations. Non-significant variables were then removed from the models and a final version run. Table 2 provides the models, the number of data points used for the final model (n), the r^2 values and root mean square error (RMSE) in ml for each model. Variables in the models were significant at the $\alpha = 0.05$ level.

4. Discussion

In general, the results in Table 2 indicate that the models for males tended to have similar or higher r^2 values than the female models. This may be due to the fact that there was more variation in $\dot{V}O_2$ values for males due to the wider ranges of forces and loads studied as well as higher mean body weight. The female models had smaller RMSE values due to the lower $\dot{V}O_2$ values.

Although the models published by Garg *et al.* (1978) are widely used to evaluate energy expenditure of various jobs, the models cannot be used to evaluate cart pushing or pulling. To predict energy expenditures during dynamic pushing and pulling, ergonomists who utilise Garg *et al.* models may incorrectly approximate the dynamic task evaluation with the pushing or pulling force measured during holding the cart in motion as the input force variable in the predictive equation of pushing or pulling items at bench height or 1.5 m while the subject is stationary (Garg *et al.* 1978, Equations 18 and 19). However, the present study developed separate equations for cart pushing and pulling that fill this void in the ergonomic literature.

The pushing and pulling models for males and the pulling model for females included a term for treadmill (TRED), although it is realised that this term will not be used for industrial activities. However, the treadmill was instrumental in studying longer pushes and pulls due to the limitation of the pushcart, which was tethered to the water reservoir. For the purposes of workplace application, this term can be deleted since the treadmill was assigned a value of 1 for the dummy variable used during modelling and the cart was assigned 0. The pushing and pulling model r^2 values were among the higher values of all models for both males and females.

Table 2. Oxygen consumption models.

Task type	Model	n	r ²	RMSE (ml)
Male				
Low lift	$\dot{V}O_2 = -716.8 + 10.3BW + 109.2BOX + 58.4FREQ + 20.8LOAD$	251	0.70	183.3
Centre lift	$\dot{V}O_2 = -731.8 + 8.8BW + 99.9BOX + 50.0FREQ + 20.0LOAD$	269	0.80	126.5
Low lower	$\dot{V}O_2 = -597.5 + 9.2BW + 100.2BOX + 65.8FREQ + 26.0LOAD$	248	0.58	256.3
Centre lower	$\dot{V}O_2 = -835.2 + 9.0BW + 76.4BOX + 72.1FREQ + 33.5LOAD$	258	0.80	157.6
Pushing	$\dot{V}O_2 = -1036.5 + 7.2BW - 108.0TRED + 60.0FREQ + 34.5 FREQDIS + 61.4FMEAS$	364	0.73	214.6
Pulling	$\dot{V}O_2 = -1205.9 + 11.1BW - 172.0TRED + 46.6FREQ + 38.7 FREQDIS + 56.8FMEAS$	280	0.78	207.7
(De)palletising	$\dot{V}O_2 = -371.6 + 7.1BW + 64.5FREQ + 39.1LOAD$	362	0.65	206.1
Carry-lower	$\dot{V}O_2 = -600.0 + 9.0BW + 68.1FREQ + 35.1FREQDIS + 23.8LOAD$	266	0.68	198.5
Carry-place	$\dot{V}O_2 = -792.1 + 9.2BW + 55.9FREQ + 37.0FREQDIS + 20.7LOAD$	307	0.67	183.8
Carry-lift	$\dot{V}O_2 = -697.3 + 9.3BW + 40.7FREQ + 35.4FREQDIS + 29.0LOAD$	286	0.74	169.6
Lift-carry-lower	$\dot{V}O_2 = -899.1 + 9.0BW + 184.7FREQ + 35.0FREQDIS + 36.7LOAD$	274	0.68	294.8
Lift-carry-place	$\dot{V}O_2 = -775.0 + 9.5BW + 53.8FREQ + 48.1FREQDIS + 31.3LOAD$	260	0.73	205.1
Lift-carry-lift	$\dot{V}O_2 = -751.6 + 8.7BW + 122.9FREQ + 32.6FREQDIS + 40.4LOAD$	303	0.71	228.3
Lower-carry-lower	$\dot{V}O_2 = -606.0 + 7.7BW + 77.2FREQ + 39.0FREQDIS + 26.3LOAD$	297	0.67	216.2
Lower-carry-place	$\dot{V}O_2 = -680.4 + 9.7BW + 22.1FREQ + 35.3FREQDIS + 20.6LOAD$	295	0.72	164.0
Lower-carry-lift	$\dot{V}O_2 = -733.9 + 7.9BW + 70.7FREQ + 40.1FREQDIS + 26.5LOAD$	248	0.78	160.8

(continued)

Table 2. (Continued).

Task type	Model	n	r ²	RMSE (ml)
Female				
Low lift	$\dot{V}O_2 = -232.5 + 4.8BW + 127.3BOX + 54.1FREQ + 34.4LOAD$	173	0.54	173.9
Centre lift	$\dot{V}O_2 = -308.7 + 5.9BW + 61.8BOX + 26.8FREQ + 37.5LOAD$	188	0.70	109.6
Low lower	$\dot{V}O_2 = -415.5 + 7.0BW + 50.1BOX + 52.5FREQ + 28.9LOAD$	148	0.60	151.7
Centre lower	$\dot{V}O_2 = -251.5 + 6.2BW + 48.8BOX + 20.1FREQ + 19.6LOAD$	190	0.66	90.3
Pushing	$\dot{V}O_2 = -864.1 + 6.4BW + 55.8FREQ + 24.4 FREQDIS + 61.0FMEAS$	245	0.79	129.5
Pulling	$\dot{V}O_2 = -891.4 + 9.1BW - 83.0TRED + 39.3FREQ + 34.3 FREQDIS + 41.9FMEAS$	210	0.82	132.3
(De)palletising	$\dot{V}O_2 = -568.5 + 12.3BW - 57.6DEPAL + 40.3BOX + 46.8FREQ + 25.9LOAD$	221	0.75	138.1
Carry-lower	$\dot{V}O_2 = -504.0 + 11.1BW + 18.2FREQ + 18.9FREQDIS + 22.3LOAD$	260	0.65	146.6
Carry-place	$\dot{V}O_2 = -275.4 + 8.7BW + 16.2FREQDIS + 14.0LOAD$	267	0.65	126.1
Carry-lift	$\dot{V}O_2 = -334.3 + 8.6BW + 14.2FREQ + 16.7FREQDIS + 26.5LOAD$	264	0.62	137.0
Lift-carry-lower	$\dot{V}O_2 = -657.9 + 12.8BW + 51.7FREQ + 21.9FREQDIS + 27.5LOAD$	262	0.67	179.1
Lift-carry-place	$\dot{V}O_2 = -541.2 + 11.7BW + 34.0FREQ + 18.6FREQDIS + 23.3LOAD$	253	0.70	143.4
Lift-carry-lift	$\dot{V}O_2 = -413.8 + 9.4BW + 44.0FREQ + 18.6FREQDIS + 33.3LOAD$	245	0.65	152.5
Lower-carry-lower	$\dot{V}O_2 = -412.8 + 9.8BW + 29.7FREQ + 18.6FREQDIS + 26.7LOAD$	251	0.69	134.6
Lower-carry-place	$\dot{V}O_2 = -318.7 + 9.1BW + 16.4FREQDIS + 20.2LOAD$	260	0.63	134.1
Lower-carry-lift	$\dot{V}O_2 = -232.8 + 6.7BW + 10.7FREQ + 21.2FREQDIS + 28.5LOAD$	225	0.72	118.1

$\dot{V}O_2$ = oxygen consumption (ml), BW = body weight (kg), BOX = 1 for large box or 0 for small box, FREQ = repetitions per min, LOAD = box weight (kg), DEPAL = 1 for depalletising or 0 for palletising, TRED = 1 for treadmill or 0 for pushcart, FREQDIS = frequency (per min) $\times$ distance (m), FMEAS = measured sustained force (kg).

The r^2 values for the nine models for combination tasks involving a carry ranged between 0.67 and 0.78 for males and between 0.62 and 0.72 for females, all within a generally close range. As mentioned earlier, the distance by frequency interaction term was added during the modelling process, resulting in distance dropping out of the model. However, the units of this term are m/min and reflect the actual rate of carrying or pushing/pulling; thus, it is not surprising that distance dropped out of the model. Frequency dropped out of two female models (carry-place) and one male model (lower-carry-place).

Interestingly, a few equations for female participants were different from male participants (Table 2). The variable (TREAD) was a factor in the pushing equation for males but not for the females. Also, for (de)palletising, factors such as the dimensions of the box and DEPAL were influential in women compared to men. Furthermore, for a combined MMH activity, such as lower-carry-place, repetitions per min was not a factor in female participants but was incorporated in the men.

The models for centre lift and lower were higher than the respective models for low lift and low lower for both males and females. Although anecdotal, this may have been due to more variation in technique between subjects for the low range. The low range required stooping and it appeared that subjects used slightly different techniques, such as how much movement there was between repetitions. For example, some subjects did not return to a full erect posture after each lift or lower and thus may have increased the metabolic cost of the task. However, the models predict average $\dot{V}O_2$ so the effect of technique will be minimised.

Body weight was a significant predictor variable in all models studied, with values ranging from 4.8 to 12.8 ml per 1 kg increase in body weight. This has significant implications given that the mean (SD) body weight of 72.4 kg (14.4) for females and 92.3 kg (15.6) for males indicates a fairly wide range of effects of body weight on $\dot{V}O_2$. For comparison, the mean (SD) body weight of the subjects studied by Garg *et al.* (1978) was 66.7 kg (12.9) for females and 75.5 kg (15.3) for males. Ciriello *et al.* (1993) reported a mean (SD) body weight of 81.8 kg (14.6) for males and this study was conducted in the same laboratory as the current study and subjects were recruited in a similar manner. These results clearly show a trend of increasing body weight, which ultimately results in a mean increase in $\dot{V}O_2$ given all other parameters are held constant. One advantage of the models reported here are that they were developed with a group of subjects whose anthropometrics were more representative of the current workforce than previous studies.

In terms of body composition, Lyons *et al.* (2005) demonstrated a greater influence of body composition in men during heavy load-carriage (40 kg vs. no load or 20 kg) compared to the total body mass. These authors expressed body composition as the ratio of lean body mass over dead mass (defined as fat mass + external workload). Although the body composition of the participants was not measured or included as a predictor variable in the models and subjects were tested only for loads ≤ 25 kg, based on the findings of Lyons *et al.* (2005), it might suffice to say that energy expenditures for ≤ 20 kg can account for participants with different body composition. However, one should not discount the fact that influence of lean body mass or fat free mass may have an affect on prediction of energy expenditures.

4.1. Limitations

As with many models, the major limitations of the models reported here are the range of tasks and task parameters studied and the subsequent range of conditions to which the

models can be applied. The goal was to provide a set of models that apply to a wide range of commonly encountered materials handling tasks with the realisation that not all situations will be accommodated. For instance, the palletising models only included one fixed distance between the pallet and origin/destination and some (de)palletising tasks in industry require, for example, a longer carry distance. Likewise, the tasks were carried out in a controlled and highly repetitive laboratory setting and the workplace often offers more diversity in terms of how tasks are performed. However, the subjects averaged 221 measurements each during the study, which took approximately 4 years to complete; thus, the demands on more conditions needs to be offset by practical issues.

Additional research will be required to estimate the accuracy of these models under realistic workplace conditions. This will provide the opportunity to explore the effects of potential limitations mentioned in the previous paragraph, as well as to assess the accuracy of the predictions.

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Appendix 1. Task parameters

Lifting and lowering parameters.

Frequency (per min)	Load (kg)	Box size	Lift/Lower Vertical Location
4.3	2.5	Small	Low: 51 cm lift/lower between floor and knuckle
4.6	5	Large	
5	10		Centre: 51 cm lift/lower between knuckle and shoulder
5.5	15		
6	20		
6.7	25		
7.5			
8.6			
10			
12			
15			

Pushing and pulling parameters.

Frequency (per min)	Load (kg)	Push/Pull Distance
0.7	10	3.8 m
0.8	12.5	7.6 m
1.0	15	15.2 m
1.1	20	
1.2	2	
1.5		
1.7		
2.0		
2.2		
2.5		
2.7		
3.0		
3.3		
3.5		
3.8		
4.0		
4.3		
4.6		
5.0		
5.5		
6.0		
6.7		

(De)Palletising parameters.

Frequency (per min)	Load (kg)	Box size
4.3	2.5	Small
4.6	5	Large
5.0	10	
5.5	15	
6.0		
6.7		
7.5		
8.6		
10		
12		
15		

Lift-carry-lower parameters.

Frequency (per min)	Load (kg.)	Lift/Lower Vertical Origin (cm)	Lift/Lower Vertical Destination (cm)	Carry Distance (m.)
1.0	2.5	Shoulder	Shoulder	2.1
1.2	5	Knuckle	Knuckle	4.3
1.3	10	Floor	Floor	8.5
1.5	15			
1.7	20			
2.0	25			
2.2				
2.5				
2.7				
3.0				
3.3				
3.5				
4.0				
4.3				
4.6				
5.0				
5.5				
6.7				
7.5				