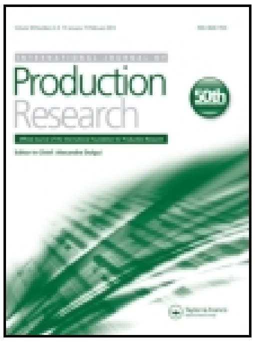

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Ergonomics in assembly line balancing based on energy expenditure: a multi-objective model

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In many assembly systems, ergonomics can have great impact on productivity and human safety. Traditional assembly systems optimisation approaches consider only time and cost variables, while few studies include also ergonomics aspects. In this study, a new multi-objective model for solving assembly line balancing problem is developed and discussed in order to include also the ergonomics aspect. First, based on main features of assembly workstations, the energy expenditure concept is used in order to estimate the ergonomics level, thanks to a new technique, called Predetermined Motion Energy System, which helps rapidly estimate the energy expenditure values. Then, a multi-objective approach, based on four different objective functions, is introduced in order to define the efficient frontiers of optimal solutions. To complete the study, a simple numerical example for a real case is presented to analyse the behaviour of Pareto frontiers varying several parameters linked to the energy and time value.

Keywords: assembly line balancing; ergonomics; multi-criteria decision-making; optimisation

1. Introduction and background

In the modern industrial systems, manual assembly is one of the most important phases of production, due to several factors: it is composed by higher added value tasks, it is strictly connected to the final market, and it requires high level of flexibility and final product quality, especially in just-in-time context (Dolgui and Proth 2010). Ideally all tasks are performed by highly qualified operators, but in reality, the always increasing need for economic solutions is driving the companies to move their assembly phases in low-cost labour countries, which comes with a low level of flexibility, due to very long distance between production stage and market, and often with lower level of quality of final products, due to lower skills and experience of employers.

For these reasons, in the last years, many companies in Europe and USA have brought back the assembly systems, moving them near the referred markets, in order to be more flexible, more efficient, with higher quality level and to reduce the cost of the transportation and the inventories of final items.

In these countries, where the cost of labour is very relevant, a particular attention is paid to the classical assembly line balancing problems, in order to obtain the maximum productivity from the assembly lines which would guarantee the required flexibility. Thus, the manual assembly lines and assembly line balancing problems are very relevant not only for emerging economies but also for developing countries.

It is well known that assembly operations have a high incidence of manual activities, especially in manual assembly systems with low presence of automated tools and manual assembly systems for big products. For example, in this kind of assembly systems, the operators perform their activities mainly using the upper body and arms, or walking across and inside the work stations, pick up the components to be assembled in unit load stocked in the floor.

The repetitive movements, the high level of physical stress and the presence of awkward postures are typical in manual assembly activities.

As a consequence, there is strictly a correlation between assembly system design and ergonomics level of workstations, due to the direct link among manual assembly tasks and the appearance of work-related musculoskeletal disorders.

For this reason, in the last years, the well-being of the assembly operators has been widely studied and a recent research of the authors (Battini et al. 2011; Battini, Persona, and Sgarbossa 2014a, 2014b) have demonstrated a link between productivity and ergonomics in assembly systems, where including the ergonomics evaluations in the human operations analysis is a win–win approach due to the interaction between productivity, motion efficiency and operational safety.

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As well known, the application of ergonomics assessment methods in assembly system design and management allows the improvement of workers conditions, quality of products and their productivity, limiting the appearance of occupational injuries and then minimising their related costs (Neumann et al. 2002; Finnsgård et al. 2011; Asensio-Cuesta et al. 2012; Cohen 2012; Finnsgård and Wänström 2013).

Usually, in the traditional approaches, the design of assembly system, made by industrial engineers in the early stage of assembly system life cycle, is separated by the evaluation of ergonomics levels of workstations, performed by medical specialists when the system is working, with a lot of limitations especially in the overall productivity (Battini et al. 2011).

The methodological framework introduced in Battini et al. (2011) permits to combine the competences of engineers and ergonomists in order to approach to the design and management of assembly systems, with a global point of view considering both operational and ergonomics aspects.

Many ergonomics evaluation techniques have been developed: self-assessment evaluation techniques, observation methods through video recordings or software tools to compute ergonomics indexes (RULA, REBA, OCRA, OWAS, Cube Model, etc.), electromyography analysis (EMG) and spectroscopy-derived measures (i.e. near-infrared spectroscopy) to investigate the effects of power tool-induced torque reaction and work–rest pattern (Li and Buckle 1999; Van Lingen et al. 2002; David 2005; Andreoni et al. 2009; Morse, Kros, and Scott Nadler 2009).

Generally, it is well known that all these methods give semi-quantitative indices and they are typically applied to study macro-activities and not to single tasks as assembly an item. Several researches have been developed in the last years in order to include these methodologies in the ALBP (Kazmierczak, Winkel, and Westgaard 2004; Otto and Scholl 2011; Bautista et al. 2013; Battini, Persona, and Sgarbossa 2014a) mainly introducing added constraints or defining multi-objective functions in the problem formulations based on traditional ergonomics evaluations.

Some limitations of these models are about the required time to estimate correctly the ergonomics levels of all the activities and the different results obtained using different ergonomics techniques.

The previous developed models, which include the ergonomics aspects into the traditional ALBP (McMullen and Frazier 1998; Otto and Scholl 2011; Bautista et al. 2013), introduce the ergonomics via non-linear constraints or objective functions. Thus, the computational complexity increases. For these reasons, in order to reduce the increasing of computational complexity, due to non-linear aspects of the problem, Otto and Scholl (2011) proposed a two-stage heuristic from SALBP-1 followed by a simulated annealing technique integrated with a local search algorithm.

In contrast, the main purposes of this study introducing a different ergonomics evaluation technique in the assembly balancing problem are as follows:

- to simplify the ergonomics assessment of each assembly task to reduce the time spent to calculate the ergonomics level;
- to use these easily to estimate ergonomics factors to reduce the complexity of the problem and consequently to be able to use the traditional assembly line balancing methods with a lower computational complexity;
- to carry out an extensive analysis of the Pareto frontiers of this multi-objective problem in order to better understand the relationship between time and ergonomics optimisation.

The here mentioned ergonomics evaluation method has been introduced by Garg, Chaffin, and Herrin (1978) and it is based on the energy expenditure assessment of standard operations execution, as a function of oxygen consumption. Its simplicity has allowed its wide use in many sectors, such as medical, military and industrial (Garg, Chaffin, and Herrin 1978; Waters et al. 1994; Sharp, Rosenberger, and Knapik 2006). The formulations introduced by Garg, Chaffin, and Herrin (1978) allow to estimate the energy expenditure of each single task execution, such as lowering or lifting an item, picking an item from a certain distance, walking or standing in a fixed position and others. They are very similar to the traditional time estimation techniques, such as predetermined time motion systems (PTMS), where the total time to perform a task is the sum of standard predetermined times, that are functions of singular movements which compose the analysed operation.

Thus, in this study, for the first time in the literature, we use the energy expenditure rate developed by Garg, Chaffin, and Herrin (1978) (measured in kcal/movement) in order to assess the ergonomic level of each assembly task. We provide a sort of 'Predetermined Motion Energy System' (PMES), very similar to classical PTMS such as MTM or MOST, well known by operations managers and practitioners (see Appendix 1), meant to lead to an easy computation of the energy expenditure per each task.

Then, we introduce a multi-objective ALBP model in which the time and energy are considered. The model is based on smoothness indices and maximal station loads to study the Pareto frontiers' shape. A numerical example illustrating both the application of PMES and proposed multi-objective approach is given. At the end, a deep parametric analysis is provided according to the variations of the following parameters: energy–time Ratio (ET) and energy–time coefficient of determination (R^2) in order to understand the different efficient frontier patterns and analyse the impact of moving from traditional time-optimal solutions to energy-optimal solutions.

The rest of the study is organised as follows: Section 2 presents in detail the energy expenditure formulations and new PMES. In Section 3, the problem context and main assumptions are introduced and the multi-objective ALBP theoretical model is described. Here, the methodology is discussed, defining the time-based and energy-based functions for the considered balancing problem. A multi-objective optimisation is given which reports Pareto frontiers to evaluate non-dominated solutions, varying the impact of energy expenditure of the assembly tasks and the relation between time and energy variables. In Section 4, a numerical example based on a real case study is used, in order to demonstrate the validity of the developed methodology. An extensive parametric analysis gives some general guidelines to help the practitioners to solve this problem in a real-life context.

At the end, several conclusions are presented to summarise the contribution of this work, discussing some limitations of the proposed approach and introducing some perspectives of this research.

2. Energy expenditure rate and PMESs

As discussed in the previous section, all traditional ergonomics evaluation methods, such as OCRA, NIOSH, OWAS, RULA, give typical risk index based on semi-quantitative evaluation of postures, movements and loads, and they are very time consuming, because they require the evaluation of many body-parts positions for each analysed posture.

In this research, we apply an alternative method developed by Garg, Chaffin, and Herrin (1978) using the analytical ergonomic measurement systems based on oxygen or metabolic consumption, where each movement features a specific energy expenditure. Then, several tables are introduced defining a new technique, called PMESs, to help the users to quickly estimate the ergonomics level of analysed jobs.

2.1 *Energy expenditure formulations*

This section reports the formulas used in our model for the determination of the energy expenditure rate, they are based on approach developed by Garg, Chaffin, and Herrin (1978). The total average metabolic consumption is determined as the sum of the energy consumptions for each movement that compose the job and for the maintenance of body postures, averaged over the total time of the job. This formula derives from the assumption that a job can be divided into simple activities and that each of them has its metabolic cost that can be calculated with the proper formulas. According to Garg, Chaffin, and Herrin (1978), the net metabolic energy expenditure is influenced by gender, body weight, load weight, vertical heights of lifting/lowering, lateral movements of arms in horizontal plane, speed of walking and carrying load, postures and time duration of the job. Other variables, such as age, training, size of load, speed of performing, temperature and humidity, have a smaller influence compared to the others aforementioned, so they are not taken into account in the model.

Notations

$\dot{E}_{\text{pos}-i}$	Metabolic energy expenditure rate due to maintenance of ith posture (kcal/min) – Sitting $\dot{E}_{\text{pos}} = 0.023 \cdot \text{BW}$ Standing $\dot{E}_{\text{pos}} = 0.024 \cdot \text{BW}$ Standing, bent position $\dot{E}_{\text{pos}} = 0.028 \cdot \text{BW}$
t_i	Time duration of ith posture (min)
ni	Total number of body posture employed in the job
$\Delta E_{\text{mov}-i}$	Net metabolic energy expenditure of the ith movement in steady state (kcal)
n	Total number of movements performed in the job
T	Time duration of the job (min)
BW	Body weight (kg)
G	Grade of the walking surface (%)
h_1	Vertical height from floor (m); starting point for lift, end point for lower
h_2	Vertical height from floor (m); end point for lift, starting point for lower
L	Weight of the load (kg)
S	Gender; 1 for males, 0 for females
$t_{\text{mov-}i}$	Time (min) for specific ith movement
X	Horizontal movement of arms (m)

The average energy expenditure rate of the job can be computed with the following formula:

$$\bar{\dot{E}}_{job} = \frac{\sum_{i=1}^{ni} \dot{E}_{pos} \cdot t_i + \sum_{i=1}^{n} \cdot E_{mov-i}}{T} \tag{1}$$

In the assembly line balancing problem (ALBP), it is interesting to calculate the energy expenditure for each assembly task, $\bar{E}_{job}$ in order to associate each task to the related time and energy value.

$$\bar{E}_{job} = \sum_{i=1}^{ni} \dot{E}_{pos} \cdot t_i + \sum_{i=1}^{n} \Delta E_{mov-i} \tag{2}$$

Some equations developed by Garg, Chaffin, and Herrin (1978) are reported in Appendix 1. For more details, please refer to Garg, Chaffin, and Herrin (1978).

2.2 *Predetermined Motion Energy System*

One of the most used measurement techniques of work is the Predetermined Motion Time Systems (PMTS), whereby the times of basic human movement are used to build up the time for a job. Usually, PMTS is a database of basic motion elements with related normal time values, together with a set of procedures for applying the data to analyse manual tasks and establish normal and standard times for the analysed tasks (MOST).

Following this concept, in this study, we define a new energy measurement technique called PMES. In the same way, several tables are developed in order to speed up the estimation of the energy expenditure of a task, starting from the basic human motions defined by Garg, Chaffin, and Herrin (1978).

In Appendix 1, we provide the PMES tables for the main elementary motions, and here below, we illustrate a simple example of PMES application, using them.

Example of Energy Expenditure estimation using PMES technique

An operator of 80 kg (BW = 80) has to pick a component (a steel frame) of 10 kg (L = 10) from a pallet stocked on the floor ($h_1 = 0.1$ m) at the distance of 3 metres from the workstation (the walking surface is plain). Then, he lifts the frame and puts it into the workstation at $h_2 = 1$ m.

- Movement 1: Walking (1 m/s) for 3 m to reach the pallet ($t_1 = 3$ s).
- Movement 2: Squat lift of the item of 10 kg from $h_1 = 0.1$ to $h_2 = 0.8$ m ($t_2 = 4$ s).
- Movement 3: Carrying the item for 3 m(3 s) to come back to the workstation ($t_3 = 3$ s).
- Movement 4: Arm lift of the item from $h_1 = 0.8$ to $h_2 = 1$ m ($t_4 = 2$ s)

Therefore, the job total time is 12 s.

Using the relative tables (see Appendix 1), we can estimate the energy expenditure for each part of the job as follows:

- Movement 1: from walking tables: $E1 = 2.5420 \times 3/60 + 0.3032 \times 0 \times 3/60 = 0.1271$ kcal/movement.
- Movement 2: from squat lift tables: $E2 = 0.2920 + 0.0153 \times 10 + 0.0043 \times 10 \times 0 = 0.4887$ kcal/movement.
- Movement 3: from carrying tables: $E3 = 2.7120 \times 3/60 + 1.5480 \times 3/60 + 0.0379 \times 0 \times 3/60 + 0.3032 \times 0 \times 3/60 = 0.213$ kcal/movement.
- Movement 4: from arm lift tables: $E4 = 0.0094 + 0.0064 \times 10 + (-0.0010) \times 0 \times 10 = 0.0734$ kcal/movement.

The energy for maintenance of body posture can be estimated using the equation related to standing posture: $\dot{E}_{pos} = 0.024 \times 80 = 1.92$ kcal/min.Therefore, the energy expenditure for the entire job $\bar{E}_{job}$ is the sum of these contributions.

$\bar{E}_{job} = 1.92 \times 12/60 + (0.1271 + 0.4887 + 0.213 + 0.0734) = 1.2862$ kcal/job

3. Multi-objective assembly line balancing problems

The ALBP consists of assigning tasks to stations optimising several goals, such as time, cost, profit under certain constraints (cycle time and other restrictions) as well as precedence relations are met.

This research is focused on the simple assembly line balancing problem (SALBP). The name SALBP has been introduced by Baybars (1986) because this problem deals with only one type of product. There are several standard techniques to solve SALBP minimising the cycle time or the number of stations required (Scholl 1999; Rekiek et al. 2002; Battaïa and Dolgui 2013).

In the next part of this section, the standard time-based and new energy-based SALBP models are illustrated, and then, we introduce a multi-objective approach integrating time and energy. As before mentioned, the model proposed in this study involves four different objective functions, two related to the time-based approach and two to the energy-based approach.

Since in most cases different functions yield different optimal solutions, the optimal solutions for time approach are often different from the optimal solutions for ergonomic models; thus, it is necessary to find the best way to couple the time-based objective functions with the ergonomics functions according to a multi-objective optimisation approach.

This is a typical example of multi-objective optimisation (MO) (Pareto [1906] 1971), used to support decision-making in case of a necessity to search for trade-offs between conflicting objectives. Objectives are in conflict if any improvement of one objective comes at the expense of another objective. A non-dominated solution, in the sense of Pareto, is defined as a solution where no feasible solution exists that yields a better objective while keeping the other objective fixed. On the contrary, a dominated solution implies that it is possible to find a better solution that entails no trade-off. The notion of a set of non-dominated solutions is central to multi-objective optimisation. Hence, the solution that achieves the optimal balance can be searched in a limited space (Pareto frontier) without considering the full range of all possible solutions.

3.1. *Time-based SALBP (Time-SALBP)*

As a traditional approach, where parameters are related to time variables, we considered the so-called SALBP-2 to minimise of the cycle time c for a defined number of stations. This approach is often used to increase the productivity of an assembly line.

Following the binary linear model (Scholl 1999) for a single-model serial assembly line (only one type of product is assembled), the problem starts from the collection of data regarding:

- set of tasks $V = (1,\ldots, n)$;
- precedence diagram with set of arcs A;
- task times t_j $(j \in V)$;
- required production rate or cycle time c;
- set of workstations $W = (1,\ldots, K)$.

From the mathematical point of view, a binary variable called x_{jk} is used to indicate the assignment, with 1 if task j is assigned to station k and 0, otherwise.

There are several objective functions used to evaluate the different assembly balancing solutions, mainly in order to minimise the cycle time (and so to maximise the throughput of the assembly line).

We select two objective functions for our model: the Time Smoothness Index ($SX - T$) to measure the equality of workload distribution among the stations, and the Mini-Max Station Time ($M - MST$), in order to maximise the total throughput:

$$\min SX - T = \min\sqrt{\sum_{k=1}^{K}\left(c_r - \sum_{j\in B_k} x_{jk}\cdot t_j\right)^2} \tag{3}$$

$$\min M - MST = \min\left\{\max\left\{\sum_{j\in B_k} x_{jk}\cdot t_j | k = 1\ldots K\right\}\right\} = \min(c_r) \tag{4}$$

$$\text{where}\, c_r = \max\left\{\sum_{j\in B_k} x_{jk}\cdot t_j | k = 1\ldots K\right\} \tag{5}$$

Let E_j, L_j be the earliest and latest stations, as defined in the algorithm of Patterson and Albracht (Scholl 1999), and c_r is the maximum station time among all stations.

To solve this problem, the following constraints have to be considered:

- Occurrence constraints ensuring that each task is assigned to exactly one station in its interval

$$\sum_{k\in[E_j,L_j]} x_{jk} = 1 \quad \text{for}\, j = 1,\ldots,n \tag{6}$$

- Cycle time constraints, guaranteeing the respect of cycle time c in each station

$$\sum_{j \in B_k} x_{jk} \cdot t_j = T_k \leq c \quad \text{for}\, k = 1, \ldots, K \tag{7}$$

- Precedence constraints, assuring that no task is assigned to an earlier station than its predecessor

$$\sum_{k \in [E_h, L_h]} k \cdot x_{hk} \leq \sum_{i \in [E_j, L_j]} i \cdot x_{ji} \quad \text{for}(h,j) \in A \,\text{and}\, L_h \geq E_j \tag{8}$$

where A is the set of arcs in precedence diagram, P_j is set of predecessors of task, j and F_h is set of successors of task h, as well as:

$$E_j \,\text{is the earliest station of task}\ j,\ E_j = \left\lceil \frac{\left(t_j + \sum_{l \in P_j} t_l\right)}{c} \right\rceil \tag{9}$$

$$L_h \,\text{is the latest station of task}\, h,\ L_h = m + 1 - \left\lceil \frac{\left(t_h + \sum_{l \in F_h} t_l\right)}{c} \right\rceil \tag{10}$$

3.2 *Energy-based SALBP (Energy-SALBP)*

Following the same approach used to define the time-oriented problems, we introduce two objective functions concerning the ergonomics aspect of the ALBP.

With the same information defined before about set of tasks, precedence diagram, cycle time and set of workstations, we collect all data regarding the energy expenditure of each task using the PMES technique explained in previous section.

In particular, using the equations introduced by Garg, Chaffin, and Herrin (1978), since each task j has energy expenditure,e_j, we define the following objective functions: the Energy Smoothness Index ($SX - E$), in order to reduce risks among the stations by distributing physical load among workers at a similar low level (Otto and Scholl 2011), and the Mini-Max Station Energy ($M - MSE$), in order to optimise the ergonomics level of the station with highest energy expenditure:

$$\min SX - E = \min \sqrt{\sum_{k=1}^{K} \left(E_r - \sum_{j \in B_k} x_{jk} \cdot e_j \right)^2} \tag{11}$$

$$\min M - MSE = \min \left\{ \max \left\{ \sum_{j \in B_k} x_{jk} \cdot e_j | k = 1 \ldots K \right\} \right\} = \min(E_r) \tag{12}$$

$$\text{where}\, E_r = \max \left\{ \sum_{j \in B_k} x_{jk} \cdot e_j | k = 1 \ldots K \right\} \tag{13}$$

This problem has the same constraints as the previous time-based model.

3.3 *Multi-objective SALBP model*

Here, we combine the objective functions defined for time-based and energy-based models in the previous subsections and we introduce the following multi-objective optimisation problem, given by:

$$\min\{SX-T;SX-E\}=\min\left\{\sqrt{\sum_{k=1}^{K}\left(c_r-\sum_{j\in B_k}x_{jk}\cdot t_j\right)^2};\sqrt{\sum_{k=1}^{K}\left(E_r-\sum_{j\in B_k}x_{jk}\cdot e_j\right)^2}\right\} \tag{14}$$

$$\min\{M-MST;M-MSE\}=\min\left\{\max\left\{\sum_{j\in B_k}x_{jk}\cdot t_j|k=1\ldots K\right\};\max\left\{\sum_{j\in B_k}x_{jk}\cdot e_j|k=1\ldots K\right\}\right\} \tag{15}$$

These multi-objective functions are introduced in order to compare the time-based and energy-based approaches using the same optimisation functions.

We will search for a Pareto frontier that is the set of non-dominated solutions of this bi-objective problem. The Pareto frontier can be estimated using different methods known in the literature (Marler and Arora 2004). The use of epsilon-constrained method could be one of the most suitable, while for limited set of data, all the feasible solutions could be calculated and Pareto frontier could be estimated based on its traditional definition.

As mentioned in the introduction section, the authors would not investigate about the efficacy and efficiency of the possible solving methods for this multi-objective problem, while the study's purposes are related to the analysis of Pareto frontiers and relationship between optimal solutions varying the time and energy data.

4. Numerical example and analysis

In order to analyse the results of our approach, we applied the Time- and Energy-SALBP models to a numerical example from a real-life case study. The analysed product is a small high-pressure cleaner for home and garden applications. The item is assembled in a traditional single-model assembly straight line with four workstations. The maximum cycle time is equal to 180 s. The total number of task is 17, and the time and energy expenditure of each task and the precedence diagram are reported in Figure 1. Task A is related to the loading of bottom support on the line and its set-up. Tasks B and C concern the assembly of wheels, tasks E and F are the pressure regulator insertion and task H and I consist in the fixing of handle system on the support. Other components of the bottom support are assembled in tasks D and G. Tasks J and K are related to the assembly of the pump system while task L is related to the power system. Tasks M and N concern the installation of the pump and the power system to the bottom support. Finally, tasks O and P regard the application of the front panel, while the unloading of the line is performed by task Q.

Task	t_j [s]	e_j [kcal]
A	24	0.95
B	46	2.69
C	13	0.90
D	7	0.18
E	25	1.19
F	15	0.88
G	5	0.15
H	38	1.23
I	11	0.96
J	80	4.56
K	85	5.07
L	25	1.00
M	60	1.08
N	65	1.17
O	45	0.92
P	25	0.50
Q	16	0.63

V is a virtual task (time and energy null) used to simplify the precedence diagram

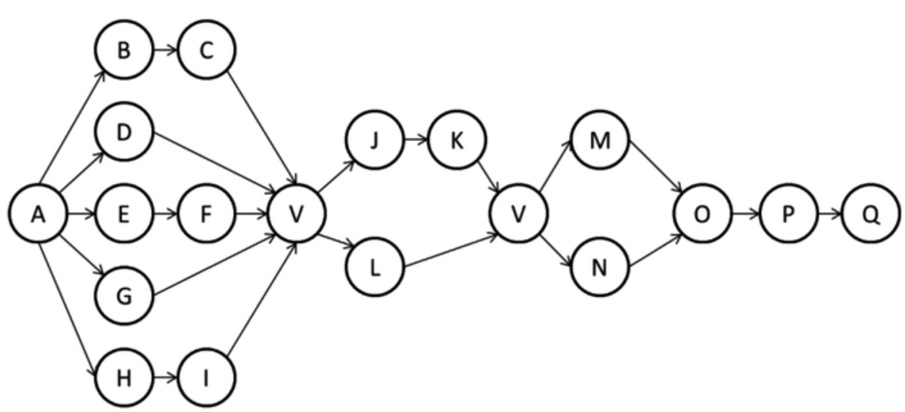

Figure 1. Precedence diagram and input data.

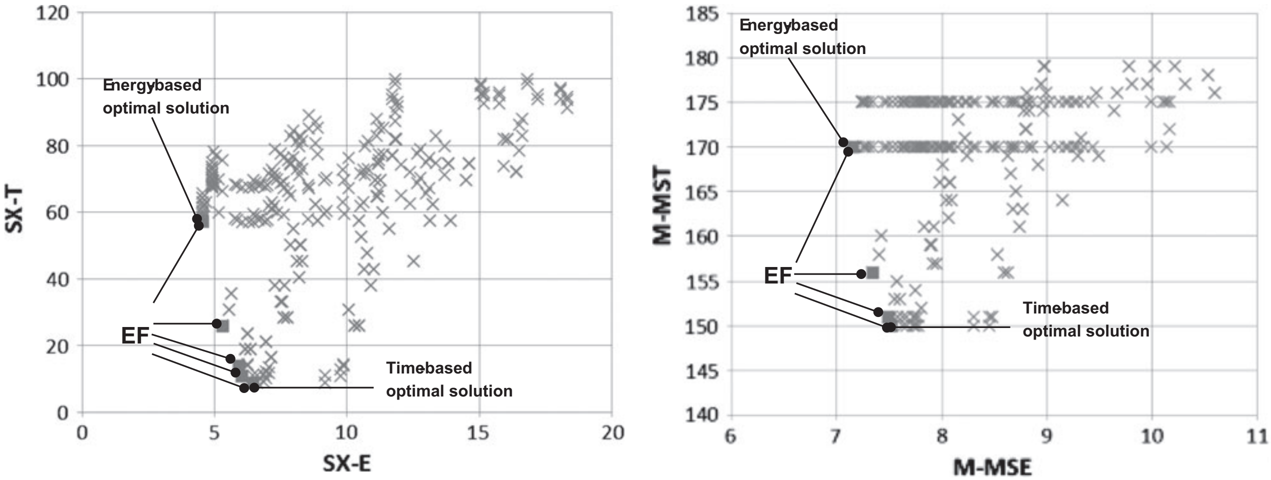

Figure 2. Feasible solutions and Pareto EFs.

We calculated the time and energy functions using the Equations (3), (4), (11) and (12), for each feasible balancing solution (crosses in Figure 2). In this case, such an enumeration is possible due to the low number of tasks. We highlighted the optimal ones (dots in Figure 2) defining the Pareto efficient frontiers (EFs) by applying formulas (14) and (15).

The EF is the set of all efficient points (dots) ranging from the time-optimal solution to the energy-optimal solution. As shown in the graphs, time and energy functions yield different balancing solutions: the optimal balancing decision depends on both time smoothness and energy smoothness and how these two objective functions evolve over the different feasible balancing solutions.

Then, the values of the Pareto EFs have been normalised with respect to the value of each objective function resulting from the optimisation of the single-objective formulations (Figure 3).

In this manner, the differences among the optimal solutions representing the EF could be expressed as percentage of the time-optimal solution and the energy-optimal ones, allowing a more general analysis.

In this case study, relating the graph concerning the smoothness indices, the EF is steep after the time-optimal solution, which means that moving from right to left on the EF will bring to a decrease in the energy smoothness and, at the same time, to a rapid increase in the time smoothness, since the time-function increases even faster. Otherwise, when the EF is flat around the time-optimal solution, with a smaller increase in time smoothness, we could obtain a more relevant decrease in energy smoothness. In Figure 3, it can be seen that the maximum difference is about 50% in energy smoothness index and more than 500% in time one.

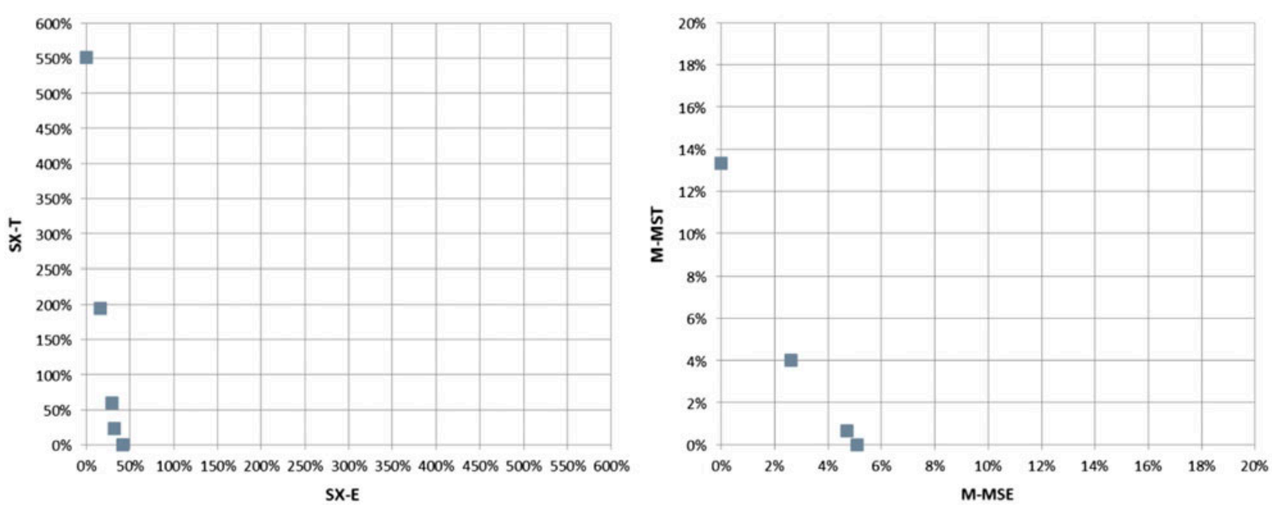

Figure 3. Normalised Pareto EFs.

More relevant outcomes can be obtained analysing the graphics. In particular, in the second graph of Figure 2, many feasible solutions are characterised by the same function value of M – MST while the energy function can vary significantly. For example, in case of the time-based optimal solution with M – MST equal to 150, the M – MSE varies from 8.45 to 7.52. This range is greater for balancing solution with higher value of M – MST.

In Figure 3, it can be noticed that the percentage differences between optimal solutions in time and energy are smaller than those obtained in case of smoothness index. This is mainly due to the definition of objective functions, as shown in Figure 2.

However, in this numerical example, the maximum station time in case of energy-optimal solution is about 13% higher than the value that results in time-optimal solution. Otherwise, the maximum station energy expenditure value obtained applying the time optimisation (4) is about 5% higher than the optimal value resulting from the energy optimisation (12).

It is important to underline how the total throughput is directly correlated to the maximum station time, so it is easy to understand the impact of the choice of EF to the productivity of the system.

We can see that, in general, the analysis of the EFs shows the relevance to consider also the ergonomics aspects in the balancing problem. In fact, if the time-based optimal solution is selected, it involves in higher values of energy-based objective functions, with possible impacts to the productivity of the assembly systems in the long-term period (Battini et al. 2011).

Moreover, it is important to analyse the Pareto Efs in order to understand how the assembly system balancing is influenced by energy and time variables in practice and to define the optimal solution comparing these two factors.

5. Parametrical analysis and discussion

As discussed in the previous section, the shape of the EFs strongly affects the final decision-making and it depends on the relationship between task time and task energy expenditures. For this reason, it is interesting to understand how the Pareto frontiers could change with the impact of the ergonomics level in the balancing problem and with the correlation between task time and energy expenditure.

Then, we introduce the ET parameter ET as the quotient between total energy expenditure and total time necessary to assembly the entire product:

$$\mathrm{ET} = \frac{\sum e_j}{\sum t_j} \tag{16}$$

In the previous numerical example, ET = 0.041.

Starting from this value, we have defined the EFs for different value of ET, such as: 0.033, 0.035, 0.037, 0.039, 0.041 and 0.043, as shown in Figure 4.

We can notice that the curves do not change its shapes, but there is only a general increase along the energy axis, which is quite obvious, since the time-based optimal balancing solutions are not affected by an increase in energy expenditure of all tasks.

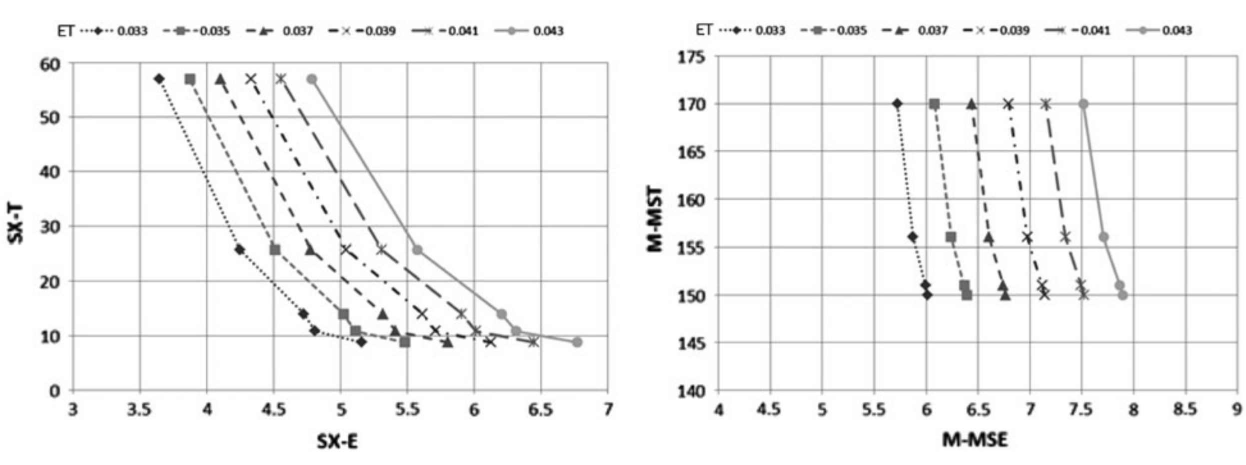

Figure 4. Sensitivity analysis of Pareto EF based on ET parameter.

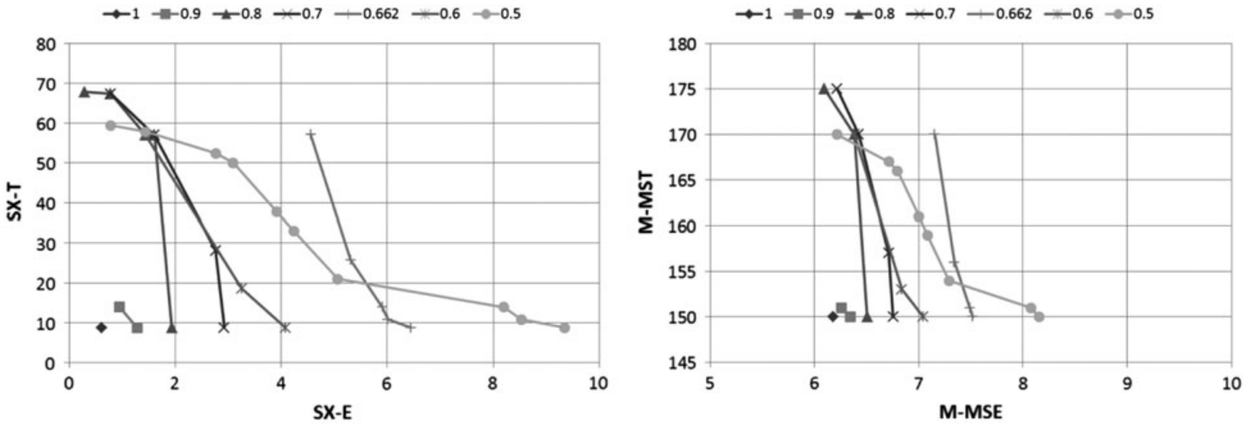

Figure 5. Sensitivity analysis of Pareto EF based on R^2 parameter.

Instead, the shape of the Pareto frontier could change if the relation between time and energy change. For this reason, we investigate the impact of the coefficient of determination (R^2) which represents how time values are related to energy values, such as the correlation between time and energy.

Usually in real context, time and energy are well correlated and the typical range of coefficients of determination is 0.6 to 1. In the analysed numerical example, the coefficient of determination $R^2 = 0.662$.

By increasing the coefficient of determination, the Pareto frontier becomes smaller. Obviously, in the ideal case of $R^2 = 1$, time and energy functions yield the same optimal balancing solution and the Pareto frontier becomes a single point. When the coefficient of determination decreases the Pareto frontier becomes larger and less steep.

Low values of R^2 are related to cases with a testing phase characterised by high processing time and low energy expenditure or where it is necessary to use a specific tool to tighten a series of screws, which requires low energy to perform a quite long task.

Generally, as noted in Figure 5, the Pareto EFs are highly influenced by the set of time and energy data. Any consideration cannot be done about the shape of the curves. In fact, there are no clear similarities among the frontiers in the analysed examples.

A particular consideration can be made about the distribution functions of time and energy data. With the coefficient of determination R^2, the correlation between data is analysed and some outcomes about the shape of Pareto frontiers are discussed. If we consider also the range of the distribution function, such as with standard deviation of data, we can obtain other interesting results. In fact, it is correct to deduce that the standard deviation impacts the size of the frontiers: higher values of standard deviation will bring to wider Pareto frontiers.

6. Conclusion and future research

In this study, we have proposed a new multi-objective approach to integrate ergonomic aspects to an assembly line balancing problem. We have considered for the first time in the line balancing literature the ergonomic measures estimated by the energy expenditure evaluation of each task execution.

To this purpose and to help practitioners, we have developed and provided a set of tables, called the PMES, similar to PMTS, which should be used for energy estimation. This permits to reduce the time spent to calculate the ergonomics measures and to simplify the ergonomics assessment of each assembly task. Moreover, the introduction of energy expenditure measurement at ergonomics level reduces the complexity of the corresponding ALBP, introducing easy to calculate ergonomics factors and allowing the application of traditional assembly line balancing methods.

Then, the multi-objective models and related Pareto EFs have been introduced integrating time and energy functions, in particular the time and energy smoothness and time and energy mini-max station quantity.

We have finally provided a parametrical analysis according to variations in the following parameters: ET and energy–time coefficient of determination in order to understand the different EF patterns and analyse the impact of moving from a traditional time-optimal solution to an energy-optimal solution.

The application to a real case study has demonstrated that the issue is a typical trade-off problem between time and energy optimisation, so the optimal time-based balancing brings to different solution for optimal energy-based one. The analysis of the Pareto frontiers, whose shape is impacted by the correlation between time and energy variables, gives useful information to the practitioners in order to understand how the selection of the balancing solution rather than others impacts on the productivity of the system and on the ergonomics level of the operators.

Several considerations are necessary about the standard deviation of time and energy and their relations, as they will impact the sensibility of the Pareto frontier and the influence of the variables.

Finally, our approach based on the energy expenditure permits to solve one of the main questions, highlighted in Otto and Scholl (2011), concerning how to estimate the monetary equivalent of ergonomics risks. In fact, in the next step of our research, we will investigate the conversion of the energy expenditure rate into rest-allowance times thanks to the formulations introduced by Rohmert (1973), to express both task times and rest times in the same unit of measure using a single-objective function based on time.

Finally, further analysis will be carried out about the impact of the number of stations to the EFs. Then, we will extend the PMES to estimate the real applied strength through the application of electromyography and to define new equations similar to those introduced by Garg, Chaffin, and Herrin (1978).

Highlights:

- New technique for ergonomics assessment called PMES.
- Simplify the ergonomics assessment of each assembly task.
- Develop a multi-objective approach for assembly balancing problem.
- Carry out an in-depth analysis of the Pareto frontiers.
- Applies the model to a real case study.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Andreoni, G., M. Mazzola, O. Ciani, M. Zambetti, M. Romero, F. Costa, and E. Preatoni. 2009. “Method for Movement and Gesture Assessment (MMGA) in Ergonomics.” In *Digital Human Modeling*, edited by V. G. Duffy, 591–598. Springer: Heidelberg.

Asensio-Cuesta, S., J. A. Diego-Mas, L. V. Cremades-Oliver, and M. C. González-Cruz. 2012. “A Method to Design Job Rotation Schedules to Prevent Work-related Musculoskeletal Disorders in Repetitive Work.” *International Journal of Production Research* 50 (24): 7467–7478.

Battaïa, O., and A. Dolgui. 2013. “A Taxonomy of Line Balancing Problems and their Solution Approaches.” *International Journal of Production Economics* 142 (2): 259–277.

Battini, D., M. Faccio, A. Persona, and F. Sgarbossa. 2011. “New Methodological Framework to Improve Productivity and Ergonomics in Assembly System Design.” *International Journal of Industrial Ergonomics* 41 (1): 30–42.

Battini, D., A. Persona, and F. Sgarbossa. 2014a. “Ergo-Balancing in Assembly Lines based on Energy Expenditure Rate.” IFORS 2014 – 20th Conference of the International Federation of Operational Research Societies, Barcelona, Spain, July 13–18.

Battini, D., A. Persona, and F. Sgarbossa. 2014b. “Innovative Real-time System to Integrate Ergonomic Evaluations into Warehouse Design and Management.” *Computers & Industrial Engineering* 77: 1–10.

Bautista, J., C. Batalla, R. Alfaro, and A. Cano. 2013. “Extended Models for TSALBP with Ergonomic Risk Constraints.” In *Proceedings of IFAC IFIP IEEE Conference on Manufacturing Modelling, Management and Control*, 869–874.

Baybars, I. 1986. “A Survey of Exact Algorithms for the Simple Assembly Line Balancing Problem.” *Management Science* 32 (8): 909–932.

Cohen, Y. 2012. “Absenteeism as a Major Cause of Bottlenecks in Assembly Lines.” *International Journal of Production Research* 50 (21): 6072–6080.

David, G. C. 2005. “Ergonomic Methods for Assessing Exposure to Risk Factors for Work-related Musculoskeletal Disorders.” *Occupational Medicine* 55 (3): 190–199.

Dolgui, A., and J. M. Proth. 2010. *Supply Chain Engineering: Useful Methods and Techniques*. London: Springer.

Finnsgård, C., and C. Wänström. 2013. “Factors Impacting Manual Picking on Assembly Lines: An Experiment in the Automotive Industry.” *International Journal of Production Research* 51 (6): 1789–1798.

Finnsgård, C., C. Wänström, L. Medbo, and W. P. Neumann. 2011. “Impact of Materials Exposure on Assembly Workstation Performance.” *International Journal of Production Research* 49 (24): 7253–7274.

Garg, Arun. Don B. Chaffin, and Gary D. Herrin. 1978. “Prediction of Metabolic Rates for Manual Materials Handling Jobs.” *The American Industrial Hygiene Association Journal* 39 (8): 661–674.

Kazmierczak, K., J. Winkel, and R. H. Westgaard. 2004. "Car Disassembly and Ergonomics in Sweden: Current Situation and Future Perspectives in Light of New Environmental Legislation." *International Journal of Production Research* 42 (7): 1305–1324.

Li, G., and P. Buckle. 1999. "Current Techniques for Assessing Physical Exposure to Work-related Musculoskeletal Risks, with Emphasis on Posture-based Methods." *Ergonomics* 42 (5): 674–695.

Marler, R. T., and J. S. Arora. 2004. "Survey of Multi-objective Optimization Methods for Engineering." *Structural and Multidisciplinary Optimization* 26 (6): 369–395.

McMullen, P. R., and G. V. Frazier. 1998. "Using Simulated Annealing to Solve a Multiobjective Assembly Line Balancing Problem with Parallel Workstations." *International Journal of Production Research* 36 (10): 2717–2741.

Morse, M., J. F. Kros, and S. Scott Nadler. 2009. "A Decision Model for the Analysis of Ergonomic Investments." *International Journal of Production Research* 47 (21): 6109–6128.

Neumann, W. P., S. Kihlberg, P. Medbo, S. E. Mathiassen, and J. Winkel. 2002. "A Case Study Evaluating the Ergonomic and Productivity Impacts of Partial Automation Strategies in the Electronics Industry." *International Journal of Production Research* 40 (16): 4059–4075.

Otto, A., and A. Scholl. 2011. "Incorporating Ergonomic Risks into Assembly Line Balancing." *European Journal of Operational Research* 212 (2): 277–286.

Pareto, V. [1906] 1971. *Manuale di economia politica, società editrice libraria* [Manual of Political Economy]. MacMillan Press: Milano. Translated and edited by A. S. Schwier.

Rekiek, B., A. Dolgui, A. Delchambre, and A. Bratcu. 2002. "State of Art of Assembly Lines Design Optimization." *Annual Reviews in Control* 26 (2): 163–174.

Rohmert, W. 1973. "Problems of Determination of Rest Allowances Part 2: Determining Rest Allowances in Different Human Tasks." *Applied Ergonomics* 4 (3): 158–162.

Scholl, A. 1999. *Balancing and Sequencing of Assembly Lines*. Heidelberg: Physica-Verlag.

Sharp, M., M. Rosenberger, and J. Knapik 2006. *Common Military Task: Materials Handling* (No. USARIEM/MN-MISC-06-31). Natick, MA: Army Research Institute of Environmental Medicine, USA.

Van Lingen, P., G. Van Rhijn, M. De Looze, P. Vink, E. Koningsveld, G. Tuinzaad, and T. Leskinen. 2002. "ERGOtool for the Integral Improvement of Ergonomics and Process Flow in Assembly." *International Journal of Production Research* 40 (15): 3973–3980.

Waters, T. R., V. Putz-Anderson, A. Garg, and National Institute for Occupational Safety and Health. 1994. Applications manual for the revised NIOSH lifting equation, 94–110. Cincinnati, OH: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Division of Biomedical and Behavioral Science.

Appendix 1.

Stoop lift (kcal/movement) – for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.325 \cdot \mathrm{BW} \cdot (0.81 - h_1) + (1.41 \cdot L + 0.76 \cdot S \cdot L)(h_2 - h_1)]$$

$$\Delta E = 10^{-2}[0.325 \cdot (0.81 - h_1)] + 10^{-2}[1.41 \cdot L \cdot (h_2 - h_1)] + 10^{-2}[0.76 \cdot S \cdot L \cdot (h_2 - \mathrm{h}_1)]$$

Stoop lift (kcal/movement) = sum of terms from the following tables

		*h*1								
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
BW	60	0.1580	0.1385	0.1190	0.0995	0.0800	0.0605	0.0410	0.0215	0.0020
	65	0.1711	0.1500	0.1289	0.1077	0.0866	0.0655	0.0444	0.0232	0.0021
	70	0.1843	0.1615	0.1388	0.1160	0.0933	0.0705	0.0478	0.0250	0.0023
	75	0.1974	0.1731	0.1487	0.1243	0.0999	0.0756	0.0512	0.0268	0.0024
	80	0.2106	0.1846	0.1586	0.1326	0.1066	0.0806	0.0546	0.0286	0.0026
	85	0.2238	0.1961	0.1685	0.1409	0.1133	0.0856	0.0580	0.0304	0.0028
	90	0.2369	0.2077	0.1784	0.1492	0.1199	0.0907	0.0614	0.0322	0.0029
	95	0.2501	0.2192	0.1883	0.1575	0.1266	0.0957	0.0648	0.0340	0.0031
	100	0.2633	0.2308	0.1983	0.1658	0.1333	0.1008	0.0683	0.0358	0.0033
To be multiple for *L*						*h*1				
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
*h*2	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.1	0.0014	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.2	0.0028	0.0014	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.3	0.0042	0.0028	0.0014	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0056	0.0042	0.0028	0.0014	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0071	0.0056	0.0042	0.0028	0.0014	0.0000	0.0000	0.0000	0.0000
	0.6	0.0085	0.0071	0.0056	0.0042	0.0028	0.0014	0.0000	0.0000	0.0000
	0.7	0.0099	0.0085	0.0071	0.0056	0.0042	0.0028	0.0014	0.0000	0.0000
	0.8	0.0113	0.0099	0.0085	0.0071	0.0056	0.0042	0.0028	0.0014	0.0000
Only for males – to be multiple for *L*						*h*1				
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
*h*2	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.1	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.2	0.0015	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.3	0.0023	0.0015	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0030	0.0023	0.0015	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0038	0.0030	0.0023	0.0015	0.0008	0.0000	0.0000	0.0000	0.0000
	0.6	0.0046	0.0038	0.0030	0.0023	0.0015	0.0008	0.0000	0.0000	0.0000
	0.7	0.0053	0.0046	0.0038	0.0030	0.0023	0.0015	0.0008	0.0000	0.0000
	0.8	0.0061	0.0053	0.0046	0.0038	0.0030	0.0023	0.0015	0.0008	0.0000

Squat lift (kcal/movement) – for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.514 \cdot \mathrm{BW} \cdot (0.81 - h_1) + (2.19 \cdot L + 0.62 \cdot S \cdot L)(h_2 - h_1)]$$

$$\Delta E = 10^{-2}[0.514 \cdot \mathrm{BW} \cdot (0.81 - h_1)] + 10^{-2}[2.19 \cdot L \cdot (h_2 - h_1)] + 10^{-2}[0.62 \cdot S \cdot L \cdot (h_2 - h_1)]$$

Squat lift (kcal/movement) = sum of terms from the following tables

		*h*1								
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
BW	60	0.2498	0.2190	0.1881	0.1573	0.1264	0.0956	0.0648	0.0339	0.0031
	65	0.2706	0.2372	0.2038	0.1704	0.1370	0.1036	0.0702	0.0368	0.0033
	70	0.2914	0.2555	0.2195	0.1835	0.1475	0.1115	0.0756	0.0396	0.0036
	75	0.3123	0.2737	0.2352	0.1966	0.1581	0.1195	0.0810	0.0424	0.0039
	80	0.3331	0.2920	0.2508	0.2097	0.1686	0.1275	0.0864	0.0452	0.0041
	85	0.3539	0.3102	0.2665	0.2228	0.1791	0.1354	0.0917	0.0481	0.0044
	90	0.3747	0.3284	0.2822	0.2359	0.1897	0.1434	0.0971	0.0509	0.0046
	95	0.3955	0.3467	0.2979	0.2490	0.2002	0.1514	0.1025	0.0537	0.0049
	100	0.4163	0.3649	0.3135	0.2621	0.2107	0.1593	0.1079	0.0565	0.0051
To be multiple for *L*		*h*1								
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
*h*2	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.1	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.2	0.0044	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.3	0.0066	0.0044	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0088	0.0066	0.0044	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0110	0.0088	0.0066	0.0044	0.0022	0.0000	0.0000	0.0000	0.0000
	0.6	0.0131	0.0110	0.0088	0.0066	0.0044	0.0022	0.0000	0.0000	0.0000
	0.7	0.0153	0.0131	0.0110	0.0088	0.0066	0.0044	0.0022	0.0000	0.0000
	0.8	0.0175	0.0153	0.0131	0.0110	0.0088	0.0066	0.0044	0.0022	0.0000
Only for males – to be multiple for *L*		*h*1								
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
*h*2	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.1	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.2	0.0012	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.3	0.0019	0.0012	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0025	0.0019	0.0012	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0031	0.0025	0.0019	0.0012	0.0006	0.0000	0.0000	0.0000	0.0000
	0.6	0.0037	0.0031	0.0025	0.0019	0.0012	0.0006	0.0000	0.0000	0.0000
	0.7	0.0043	0.0037	0.0031	0.0025	0.0019	0.0012	0.0006	0.0000	0.0000
	0.8	0.0050	0.0043	0.0037	0.0031	0.0025	0.0019	0.0012	0.0006	0.0000

Arm lift (kcal/movement) – for $0.81 < h_1 < h_2$

$$\Delta E = 10^{-2}[0.062 \cdot \mathrm{BW} \cdot (h_2 - 0.81) + (3.19 \cdot L - 0.52 \cdot S \cdot L)(h_2 - h_1)]$$

$$\Delta E = 10^{-2}[0.062 \cdot \mathrm{BW} \cdot (h_2 - 0.81)] + 10^{-2}[3.19 \cdot L(h_2 - h_1)] - 10^{-2}[0.52 \cdot S \cdot L(h_2 - h_1)]$$

Arm lift (kcal/movement) = sum of terms from the following tables

		h2											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
BW	60	0.0033	0.0071	0.0108	0.0145	0.0182	0.0219	0.0257	0.0294	0.0331	0.0368	0.0405	0.0443
	65	0.0036	0.0077	0.0117	0.0157	0.0197	0.0238	0.0278	0.0318	0.0359	0.0399	0.0439	0.0480
	70	0.0039	0.0082	0.0126	0.0169	0.0213	0.0256	0.0299	0.0343	0.0386	0.0430	0.0473	0.0516
	75	0.0042	0.0088	0.0135	0.0181	0.0228	0.0274	0.0321	0.0367	0.0414	0.0460	0.0507	0.0553
	80	0.0045	0.0094	0.0144	0.0193	0.0243	0.0293	0.0342	0.0392	0.0441	0.0491	0.0541	0.0590
	85	0.0047	0.0100	0.0153	0.0206	0.0258	0.0311	0.0364	0.0416	0.0469	0.0522	0.0574	0.0627
	90	0.0050	0.0106	0.0162	0.0218	0.0273	0.0329	0.0385	0.0441	0.0497	0.0552	0.0608	0.0664
	95	0.0053	0.0112	0.0171	0.0230	0.0289	0.0348	0.0406	0.0465	0.0524	0.0583	0.0642	0.0701
	100	0.0056	0.0118	0.0180	0.0242	0.0304	0.0366	0.0428	0.0490	0.0552	0.0614	0.0676	0.0738
To be multiple for L		h2											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
h1	0.8	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191	0.0223	0.0255	0.0287	0.0319	0.0351	0.0383
	0.9	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191	0.0223	0.0255	0.0287	0.0319	0.0351
	1.0	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191	0.0223	0.0255	0.0287	0.0319
	1.1	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191	0.0223	0.0255	0.0287
	1.2	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191	0.0223	0.0255
	1.3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191	0.0223
	1.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160	0.0191
	1.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128	0.0160
	1.6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096	0.0128
	1.7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064	0.0096
	1.8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0064
	1.9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032
	2.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Only for males – to be multiple for L		h2											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
h1	0.8	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031	−0.0036	−0.0042	−0.0047	−0.0052	−0.0057	−0.0062
	0.9	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031	−0.0036	−0.0042	−0.0047	−0.0052	−0.0057
	1.0	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031	−0.0036	−0.0042	−0.0047	−0.0052
	1.1	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031	−0.0036	−0.0042	−0.0047
	1.2	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031	−0.0036	−0.0042
	1.3	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031	−0.0036
	1.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026	−0.0031
	1.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021	−0.0026
	1.6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016	−0.0021
	1.7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010	−0.0016
	1.8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005	−0.0010
	1.9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	−0.0005
	2.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Stoop lower (kcal/movement) – for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.268 \cdot W \cdot (0.81 - h_1) + 0.675 \cdot L \cdot (h_2 - h_1) + 5.22 \cdot S \cdot (0.81 - h_1)]$$

$$\Delta E = 10^{-2}[0.268 \cdot \mathrm{BW} \cdot (0.81 - h_1)] + 10^{-2}[0.675 \cdot L \cdot (h_2 - h_1)] + 10^{-2}[5.22 \cdot S \cdot (0.81 - h_1)]$$

Stoop lower (kcal/movement) = sum of terms from the following tables

		*h*1								
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
BW	60	0.1302	0.1142	0.0981	0.0820	0.0659	0.0498	0.0338	0.0177	0.0016
	65	0.1411	0.1237	0.1063	0.0888	0.0714	0.0540	0.0366	0.0192	0.0017
	70	0.1520	0.1332	0.1144	0.0957	0.0769	0.0582	0.0394	0.0206	0.0019
	75	0.1628	0.1427	0.1226	0.1025	0.0824	0.0623	0.0422	0.0221	0.0020
	80	0.1737	0.1522	0.1308	0.1093	0.0879	0.0665	0.0450	0.0236	0.0021
	85	0.1845	0.1617	0.1390	0.1162	0.0934	0.0706	0.0478	0.0251	0.0023
	90	0.1954	0.1713	0.1471	0.1230	0.0989	0.0748	0.0507	0.0265	0.0024
	95	0.2062	0.1808	0.1553	0.1298	0.1044	0.0789	0.0535	0.0280	0.0025
	100	0.2171	0.1903	0.1635	0.1367	0.1099	0.0831	0.0563	0.0295	0.0027
To be multiple for *L*						*h*1				
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
*h*2	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.1	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.2	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.3	0.0020	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0027	0.0020	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0034	0.0027	0.0020	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000
	0.6	0.0041	0.0034	0.0027	0.0020	0.0014	0.0007	0.0000	0.0000	0.0000
	0.7	0.0047	0.0041	0.0034	0.0027	0.0020	0.0014	0.0007	0.0000	0.0000
	0.8	0.0054	0.0047	0.0041	0.0034	0.0027	0.0020	0.0014	0.0007	0.0000
Only for males						*h*1				
– to be multiple for *L*		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
S	1	0.0423	0.0371	0.0318	0.0266	0.0214	0.0162	0.0110	0.0057	0.0005

Squat lower (kcal/movement) – for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.511 \cdot \mathrm{BW} \cdot (0.81 - h_1) + 0.701 \cdot L \cdot (h_2 - h_1)]$$

$$\Delta E = 10^{-2}[0.511 \cdot \mathrm{BW} \cdot (0.81 - h_1)] + 10^{-2}[0.701 \cdot L \cdot (h_2 - h_1)]$$

Squat lower (kcal/movement) = sum of terms from the following tables

		*h*1								
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
BW	60	0.2483	0.2177	0.1870	0.1564	0.1257	0.0950	0.0644	0.0337	0.0031
	65	0.2690	0.2358	0.2026	0.1694	0.1362	0.1030	0.0698	0.0365	0.0033
	70	0.2897	0.2540	0.2182	0.1824	0.1467	0.1109	0.0751	0.0393	0.0036
	75	0.3104	0.2721	0.2338	0.1955	0.1571	0.1188	0.0805	0.0422	0.0038
	80	0.3311	0.2902	0.2494	0.2085	0.1676	0.1267	0.0858	0.0450	0.0041
	85	0.3518	0.3084	0.2650	0.2215	0.1781	0.1346	0.0912	0.0478	0.0043
	90	0.3725	0.3265	0.2805	0.2345	0.1886	0.1426	0.0966	0.0506	0.0046
	95	0.3932	0.3447	0.2961	0.2476	0.1990	0.1505	0.1019	0.0534	0.0049
	100	0.4139	0.3628	0.3117	0.2606	0.2095	0.1584	0.1073	0.0562	0.0051
To be multiple						*h*1				
for *L*		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
*h*2	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.1	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.2	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.3	0.0021	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0028	0.0021	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0035	0.0028	0.0021	0.0014	0.0007	0.0000	0.0000	0.0000	0.0000
	0.6	0.0042	0.0035	0.0028	0.0021	0.0014	0.0007	0.0000	0.0000	0.0000
	0.7	0.0049	0.0042	0.0035	0.0028	0.0021	0.0014	0.0007	0.0000	0.0000
	0.8	0.0056	0.0049	0.0042	0.0035	0.0028	0.0021	0.0014	0.0007	0.0000

Arm lower (kcal/movement) – for $0.81 < h_1 < h_2$

$$\Delta E = 10^{-2}[0.062 \cdot \mathrm{BW} \cdot (h_2 - 0.81) + (3.19 \cdot L + 0.52 \cdot S \cdot L)(h_2 - h_1)]$$

$$\Delta E = 10^{-2}[0.062 \cdot \mathrm{BW} \cdot (h_2 - 0.81)]$$

$$+10^{-2}[3.19 \cdot (h_2 - h_1)] \cdot L$$

$$+10^{-2}[0.52 \cdot (h_2 - h_1)] \cdot S \cdot L$$

Arm lower (kcal/movement) = sum of terms from the following tables

		*h*2											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
BW	60	0.0050	0.0106	0.0162	0.0218	0.0273	0.0329	0.0385	0.0441	0.0497	0.0552	0.0608	0.0664
	65	0.0054	0.0115	0.0175	0.0236	0.0296	0.0357	0.0417	0.0478	0.0538	0.0598	0.0659	0.0719
	70	0.0059	0.0124	0.0189	0.0254	0.0319	0.0384	0.0449	0.0514	0.0579	0.0644	0.0710	0.0775
	75	0.0063	0.0133	0.0202	0.0272	0.0342	0.0412	0.0481	0.0551	0.0621	0.0691	0.0760	0.0830
	80	0.0067	0.0141	0.0216	0.0290	0.0365	0.0439	0.0513	0.0588	0.0662	0.0737	0.0811	0.0885
	85	0.0071	0.0150	0.0229	0.0308	0.0387	0.0466	0.0545	0.0624	0.0704	0.0783	0.0862	0.0941
	90	0.0075	0.0159	0.0243	0.0326	0.0410	0.0494	0.0578	0.0661	0.0745	0.0829	0.0912	0.0996
	95	0.0080	0.0168	0.0256	0.0345	0.0433	0.0521	0.0610	0.0698	0.0786	0.0875	0.0963	0.1051
	100	0.0084	0.0177	0.0270	0.0363	0.0456	0.0549	0.0642	0.0735	0.0828	0.0921	0.1014	0.1107
To be multiple for *L*		*h*2											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
*h*1	0.8	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061	0.0071	0.0082	0.0092	0.0102	0.0112	0.0122
	0.9	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061	0.0071	0.0082	0.0092	0.0102	0.0112
	1.0	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061	0.0071	0.0082	0.0092	0.0102
	1.1	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061	0.0071	0.0082	0.0092
	1.2	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061	0.0071	0.0082
	1.3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061	0.0071
	1.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051	0.0061
	1.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041	0.0051
	1.6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031	0.0041
	1.7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020	0.0031
	1.8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0020
	1.9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010

(*Continued*)

(*Continued*)

Arm lower (kcal/movement) = sum of terms from the following tables

		$h2$											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
	2.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Only for males – to be multiple for L		$h2$											
		0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
$h1$	0.8	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022	0.0026	0.0030	0.0033	0.0037	0.0041	0.0044
	0.9	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022	0.0026	0.0030	0.0033	0.0037	0.0041
	1.0	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022	0.0026	0.0030	0.0033	0.0037
	1.1	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022	0.0026	0.0030	0.0033
	1.2	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022	0.0026	0.0030
	1.3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022	0.0026
	1.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019	0.0022
	1.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015	0.0019
	1.6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011	0.0015
	1.7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007	0.0011
	1.8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0007
	1.9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004
	2.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Walking (kcal/movement)

$$\Delta E = 10^{-2}\left[51 + 2.54 \cdot \mathrm{BW} \cdot V^2 + 0.379 \cdot \mathrm{BW} \cdot G \cdot V\right] \cdot t$$

$$\Delta E = 10^{-2}\left[51 + 2.54 \cdot \mathrm{BW} \cdot V^2\right] \cdot t$$

$$+10^{-2}[0.379 \cdot \mathrm{BW} \cdot V] \cdot G \cdot t$$

Walking (kcal/movement) = sum of terms from the following tables

To be multiple for t (min)		V				
		0.5	1.0	1.5	2.0	2.5
BW	60	0.8910	2.0340	3.9390	6.6060	10.0350
	65	0.9228	2.1610	4.2248	7.1140	10.8288
	70	0.9545	2.2880	4.5105	7.6220	11.6225
	75	0.9863	2.4150	4.7963	8.1300	12.4163
	80	1.0180	2.5420	5.0820	8.6380	13.2100
	85	1.0498	2.6690	5.3678	9.1460	14.0038
	90	1.0815	2.7960	5.6535	9.6540	14.7975
	95	1.1133	2.9230	5.9393	10.1620	15.5913
	100	1.1450	3.0500	6.2250	10.6700	16.3850
To be multiple for t (min) and G (%)				V		
		0.5	1.0	1.5	2.0	2.5
BW	60	0.0569	0.2274	0.5117	0.9096	1.4213
	65	0.0616	0.2464	0.5543	0.9854	1.5397
	70	0.0663	0.2653	0.5969	1.0612	1.6581
	75	0.0711	0.2843	0.6396	1.1370	1.7766
	80	0.0758	0.3032	0.6822	1.2128	1.8950
	85	0.0805	0.3222	0.7248	1.2886	2.0134
	90	0.0853	0.3411	0.7675	1.3644	2.1319
	95	0.0900	0.3601	0.8101	1.4402	2.2503
	100	0.0948	0.3790	0.8528	1.5160	2.3688

Carrying loads held against things or against waist (kcal/movement)

$$\Delta E = 10^{-2}\left[68 + 2.54 \cdot \mathrm{BW} \cdot V^2 + 4.08 \cdot L \cdot V^2 + 11.4 \cdot L + 0.379 \cdot (L + \mathrm{BW}) \cdot G \cdot V\right] \cdot t$$

$$\Delta E = 10^{-2}\left[68 + 2.54 \cdot \mathrm{BW} \cdot V^2\right] \cdot t + 10^{-2}\left[4.08 \cdot L \cdot V^2 + 11.4 \cdot L\right] \cdot t + 10^{-2}[0.379 \cdot L \cdot V] \cdot t \cdot G + 10^{-2}[0.379 \cdot \mathrm{BW} \cdot V] \cdot t \cdot G$$

Carrying loads held against things or against waist (kcal/movement) = sum of terms from the following tables

To be multiple for t (min)		V				
		0.5	1.0	1.5	2.0	2.5
BW	60	1.0610	2.2040	4.1090	6.7760	10.2050
	65	1.0928	2.3310	4.3948	7.2840	10.9988
	70	1.1245	2.4580	4.6805	7.7920	11.7925
	75	1.1563	2.5850	4.9663	8.3000	12.5863
	80	1.1880	2.7120	5.2520	8.8080	13.3800
	85	1.2198	2.8390	5.5378	9.3160	14.1738
	90	1.2515	2.9660	5.8235	9.8240	14.9675
	95	1.2833	3.0930	6.1093	10.3320	15.7613
	100	1.3150	3.2200	6.3950	10.8400	16.5550
To be multiple for t (min)				V		
		0.5	1.0	1.5	2.0	2.5
L	0.5	0.0621	0.0774	0.1029	0.1386	0.1845
	1.0	0.1242	0.1548	0.2058	0.2772	0.3690
	1.5	0.1863	0.2322	0.3087	0.4158	0.5535
	2.0	0.2484	0.3096	0.4116	0.5544	0.7380
	3.0	0.3726	0.4644	0.6174	0.8316	1.1070
	4.0	0.4968	0.6192	0.8232	1.1088	1.4760
	5.0	0.6210	0.7740	1.0290	1.3860	1.8450
	7.5	0.9315	1.1610	1.5435	2.0790	2.7675
	10.0	1.2420	1.5480	2.0580	2.7720	3.6900
	12.5	1.5525	1.9350	2.5725	3.4650	4.6125
	15.0	1.8630	2.3220	3.0870	4.1580	5.5350
	20.0	2.4840	3.0960	4.1160	5.5440	7.3800

To be multiple for t (min) and G (%)		V				
		0.5	1.0	1.5	2.0	2.5
L	0.5	0.0009	0.0019	0.0028	0.0038	0.0047
	1.0	0.0019	0.0038	0.0057	0.0076	0.0095
	1.5	0.0028	0.0057	0.0085	0.0114	0.0142
	2.0	0.0038	0.0076	0.0114	0.0152	0.0190
	3.0	0.0057	0.0114	0.0171	0.0227	0.0284
	4.0	0.0076	0.0152	0.0227	0.0303	0.0379
	5.0	0.0095	0.0190	0.0284	0.0379	0.0474
	7.5	0.0142	0.0284	0.0426	0.0569	0.0711
	10.0	0.0190	0.0379	0.0569	0.0758	0.0948
	12.5	0.0237	0.0474	0.0711	0.0948	0.1184
	15.0	0.0284	0.0569	0.0853	0.1137	0.1421
	20.0	0.0379	0.0758	0.1137	0.1516	0.1895
To be multiple for t (min) and G (%)				V		
		0.5	1.0	1.5	2.0	2.5
BW	60	0.1137	0.2274	0.3411	0.4548	0.5685
	65	0.1232	0.2464	0.3695	0.4927	0.6159
	70	0.1327	0.2653	0.3980	0.5306	0.6633
	75	0.1421	0.2843	0.4264	0.5685	0.7106
	80	0.1516	0.3032	0.4548	0.6064	0.7580
	85	0.1611	0.3222	0.4832	0.6443	0.8054
	90	0.1706	0.3411	0.5117	0.6822	0.8528
	95	0.1800	0.3601	0.5401	0.7201	0.9001
	100	0.1895	0.3790	0.5685	0.7580	0.9475

Lateral movement of arms of 180°, both hands (kcal/movement)

$$\Delta E = 10^{-2}[0.11 \cdot \mathrm{BW} + 0.726 \cdot L]$$

Lateral movement of arms of 180°, both hands (kcal/movement) = sum of terms from the following tables

	L	0.5	1.0	1.5	2.0	3.0	4.0	5.0	7.5	10.0	12.5	15.0	20.0
BW	60	0.0696	0.0733	0.0769	0.0805	0.0878	0.0950	0.1023	0.1205	0.1386	0.1568	0.1749	0.2112
	65	0.0751	0.0788	0.0824	0.0860	0.0933	0.1005	0.1078	0.1260	0.1441	0.1623	0.1804	0.2167
	70	0.0806	0.0843	0.0879	0.0915	0.0988	0.1060	0.1133	0.1315	0.1496	0.1678	0.1859	0.2222
	75	0.0861	0.0898	0.0934	0.0970	0.1043	0.1115	0.1188	0.1370	0.1551	0.1733	0.1914	0.2277
	80	0.0916	0.0953	0.0989	0.1025	0.1098	0.1170	0.1243	0.1425	0.1606	0.1788	0.1969	0.2332
	85	0.0971	0.1008	0.1044	0.1080	0.1153	0.1225	0.1298	0.1480	0.1661	0.1843	0.2024	0.2387
	90	0.1026	0.1063	0.1099	0.1135	0.1208	0.1280	0.1353	0.1535	0.1716	0.1898	0.2079	0.2442
	95	0.1081	0.1118	0.1154	0.1190	0.1263	0.1335	0.1408	0.1590	0.1771	0.1953	0.2134	0.2497
	100	0.1136	0.1173	0.1209	0.1245	0.1318	0.1390	0.1463	0.1645	0.1826	0.2008	0.2189	0.2552

Lateral movement of arms of 90°, standing one or both hands (kcal/movement)

$$\Delta E = 10^{-2}[3.31 + 0.629 \cdot L + 0.143 \cdot S \cdot L]$$

Lateral movement of arms of 90°, standing one or both hands (kcal/movement) = sum of terms from the following tables

	L	0.5	1.0	1.5	2.0	3.0	4.0	5.0	7.5	10.0	12.5	15.0	20.0
S	0	0.0362	0.0394	0.0425	0.0457	0.0520	0.0583	0.0646	0.0803	0.0960	0.1117	0.1275	0.1589
	1	0.0370	0.0408	0.0447	0.0485	0.0563	0.0640	0.0717	0.0910	0.1103	0.1296	0.1489	0.1875

Forward movement of arms, standing one or both hands (kcal/movement)

$$\Delta E = 10^{-2} \cdot X \cdot [3.57 + 1.23 \cdot L]$$

Lateral movement of arms of 180°, both hands (kcal/movement) = sum of terms from the following tables

	L	0.5	1.0	1.5	2.0	3.0	4.0	5.0	7.5	10.0	12.5	15.0	20.0
X	0.1	0.0042	0.0048	0.0054	0.0060	0.0073	0.0085	0.0097	0.0128	0.0159	0.0189	0.0220	0.0282
	0.2	0.0084	0.0096	0.0108	0.0121	0.0145	0.0170	0.0194	0.0256	0.0317	0.0379	0.0440	0.0563
	0.3	0.0126	0.0144	0.0162	0.0181	0.0218	0.0255	0.0292	0.0384	0.0476	0.0568	0.0661	0.0845
	0.4	0.0167	0.0192	0.0217	0.0241	0.0290	0.0340	0.0389	0.0512	0.0635	0.0758	0.0881	0.1127
	0.5	0.0209	0.0240	0.0271	0.0302	0.0363	0.0425	0.0486	0.0640	0.0794	0.0947	0.1101	0.1409
	0.6	0.0251	0.0288	0.0325	0.0362	0.0436	0.0509	0.0583	0.0768	0.0952	0.1137	0.1321	0.1690
	0.7	0.0293	0.0336	0.0379	0.0422	0.0508	0.0594	0.0680	0.0896	0.1111	0.1326	0.1541	0.1972
	0.8	0.0335	0.0384	0.0433	0.0482	0.0581	0.0679	0.0778	0.1024	0.1270	0.1516	0.1762	0.2254
	0.9	0.0377	0.0432	0.0487	0.0543	0.0653	0.0764	0.0875	0.1152	0.1428	0.1705	0.1982	0.2535