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Performance Appraisal of CNC Milling Operator using Energy Expenditure Prediction Program (EEPP)

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Abstract: In workstation design and evaluation, energy expenditure plays a vital role as far as the worker's safety, health and efficiency of performing tasks in the most effective and efficient manner, is concerned. This study has been carried out for finding the energy expenditure by using Energy Expenditure Prediction Program Software. The energy expenditure was determined by observing and recording the activities during the machining operations on a CNC milling machine. In this work the average metabolic energy rate is predicted by knowing the energy expenditure and task duration. The method used in this work is more accurate and feasible and less costly than laboratory techniques such as measurement of oxygen consumption, etc. The technique used in this work provides an objective rate to gauge worker fatigue.

***Index Terms* - CNC, Ergonomic, Evaluation, Energy expenditure, Worker's fatigue.**

1. Introduction

Skeletal muscles may be thought of as biochemical machines with chemical energy stored in adenosine triphosphate (ATP) going into the muscles and being converted to mechanical work and heat energy, Sherwood (1997). In other words, the total metabolic energy expenditure will be transformed mainly into the sum of the work done by the joint actuator torques, heat energy dissipation and basal metabolic energy. In the case of static load – where the mechanical work done by muscle is zero – the muscle energy is all dissipated as heat. Mechanical power is expressed as the product of joint actuator torque and joint velocity. The total mechanical power of the system is determined as the sum of mechanical power of all the joints.

Ergonomist, applied physiologist, sports scientist, nutritionist and epidemiologist require the estimates of activity patterns and energy expenditures. Methods generally used for measurement of energy expenditure are:

- 'Gold standard' method
- CosMed K4b2 (Rome, Italy) portable indirect calorimeter
- Metamax (Borsdorf, Germany)
- MedGraphics VO2000
- Accelerometer
- Portable metabolic unit
- Pedometer
- Polar heart rate monitor
- Doubly labelled water
- Multiple inertial sensors
- Motion sensors
- A combined heart rate and motion sensor
- A combined heart rate and questionnaire methods
- Integrated electromyography
- Pulmonary ventilation volume
- Thermal imaging
- Flex-heart rate method

Recent technological advancements in the sensor technology along with the great progress made in algorithms have made accelerometers a powerful technique often used to assess everyday physical activity. Energy expenditure consists of following three components,

- Maintenance expenditure
- Diet-induced energy expenditure
- Activity-induced energy expenditure

A model of muscle energy expenditure was developed for predicting thermal as well as mechanical energy liberation during simulated muscle contractions (Umberger et al, 2003). The muscle energy model was evaluated at varying levels of complexity, ranging from simulated contractions of isolated muscle, to simulations of whole body locomotion. In all cases, acceptable, agreement was found between simulated and experimental energy liberation. (Gunn et al, 2004) Investigated four self-paced household tasks (sweeping, window cleaning, vacuuming and mowing), conducted in the subjects' homes and a standardized laboratory environment. Energy expenditure was predicted via indirect methods. The findings suggest that the aforementioned household chores can contribute to the 30 minutes per day of moderate-intensity activity required to confer health benefits.

However, the substantial between-subject variability in energy expenditure resulted in some persons performing these tasks at a light intensity. The significant metabolic equivalent (MET) differences between the home and laboratory emphasize the effects of 'environment and terrain' and the 'mental approach to a task' on self-paced energy expenditure. Levine (2005) reviewed and assessed metabolic needs, fuel utilization, and the relative thermic effect of different food, drink, drug and emotional components for measurement of energy expenditure in humans. He recommended that, for high accuracy with sufficient resource availability, an open-circuit indirect calorimeter can be used, whereas when resources are limited and/or optimum precision can be sacrificed, flexible total collection systems and non-calorimetric methods are potentially useful if the limitations of these methods are appreciated. For detailed information on free-living subjects' factorial method is used. Przybyszewski (2011) predicted energy expenditure from physical activity (PA), heart rate (HR) and anthropometry in female Indian tea pluckers. An energy expenditure (EE) prediction equation was generated using a branched method that first distinguishes time during normal workday activities (resting, plucking and walking) using accelerometer counts. Resting EE was estimated from age and weight, while minute-by-minute non-resting EE was estimated from HR and body mass index (BMI). He concluded that energy expenditure can be accurately predicted with a branched equation based on the PA, HR, age, weight, and height for a specific population participating in a known set of activities. Very little is known about the longitudinal changes in energy requirements in late life Cooper et al. (2013). The purposes of this study were to determine: (i) the energy requirements in late life and how they changed during a 7-year time-span, (ii) whether changes in fat free mass (FFM) were related to changes in resting metabolic rate (RMR), and (iii) the accuracy of predicted total energy expenditure (TEE) to measure TEE. He concluded that TEE, RMR and activity energy expenditure (AEE) decreased in men, but not in women, from the 8th to 9th decade of life. The Dietary Reference Intake (DRI) equation to predict TEE was comparable to measured TEE, while the DRI equation proposed by the World Health Organization (WHO), over-predicted TEE in an elderly population. Non-calorimetric methods proposed by Ocobock (2014) for estimating energy expenditure are often used due to their ease of use and relative economy. These methods estimate energy expenditure through physiological variables that are related to energy expenditure such as heart rate and muscle activity. These methods have been standardized and validated using calorimetric methods. Levine (2005) has used five methods for energy expenditure measurements, namely, integrated electromyography, pulmonary ventilation volume, thermal imaging, flex-heart rate and the doubly labelled water. The model as presented by Ocobock (2014) for predicting human total energy expenditure (TEE), the Factorial Method significantly underestimates actual TEE, particularly among highly active populations. In this study, the Allocation Model is presented for predicting TEE. Unlike the Factorial Method, the Allocation Model includes metabolic cost terms for both thermoregulation and the thermic effect of food, as well as using more accurate basal metabolic rate and activity cost estimations. The Allocation Model was tested using doubly labelled water and flex-heart rate measured TEEs of healthy, highly active adults. The results suggest the Allocation Model is a powerful new tool that should be used in place of the Factorial Method for estimating human TEE, and can be used to analyse adaptations, life history strategies and differential energy allocation among highly active humans in natural environments. The energy expenditure prediction program software technique provides an objective rate to gauge workers' fatigue (Mohsin et al., 2016).

2. METHODS

A: Experimental Setup

The experimental setup is shown in Fig.1. The subject for the experiment was selected on the basis of various cognitive tests. For this cognitive test, Design Tools Laboratory Software as proposed by (Niebel and Freivalds, 2001) was used.

The results of various cognitive tests are presented below:

(i) Simple reaction time (RT) Results

Color	Average Response Time (Seconds)	Standard Deviation
Blue	0.4055	0.0157
Green	0.4031	0.0280
Red	0.3969	0.0178
Yellow	0.4023	0.0638

(ii) Fitts Tapping Task Results

Average Tapping Time: 0.5228 Sec.
Standard Deviation: 0.0000

(iii) Psychophysics Experiment Results

Average Response Time: 1.3516 Sec.
Standard Deviation: 0.3895

(iv) Short Term Memory Span Results

Length	No of Correctly Recalled
5	5

(v) Stroop Test Results

Stimulus Color	No of RTs	Errors	Mean RT (Sec.)	Std. Dev. RT
Red	1	0	1.1836	0.0000
Aqua	7	0	0.8404	0.2688
Green	2	0	1.2461	0.3094
Blue	0	0	0.2461	0.0000

(vi) Visual Inspection Results

Average Response Time: 1.7112 Sec.
Standard Deviation: 1.0232

The above results indicate that the subject selected for the concerned experiment is successful in the above test conducted and fit for the given task.

In this work a computerized numerical controlled machine setup was used for the experiment. The Computer Numerical Control (CNC) machine setup includes the computer, CNC milling machine and a rack for putting raw and finished material in a closed chamber Fig. 1. The experiment was performed in the CIM lab, Department of mechanical engineering, Zakir Husain College of Engineering and technology Aligarh Muslim University, Aligarh, India. The average dry bulb temperature was 23.25˚C and the average wet bulb temperature was 20.5˚C. Illumination level maintained was 30 fc. A reflection of the light from windows and door was eliminated through proper coverings. Sound level throughout the experiment is recorded and is found within the acceptable limit 79.97 dBA and verified by the *Design Tools Laboratory Program*. Figure 2 shows that the operator is sitting on a comfortable chair while entering and simulating the CNC program. Figure 3 shows that the subject is standing in front of the CNC machine at a comfortable distance for performing the experiment.

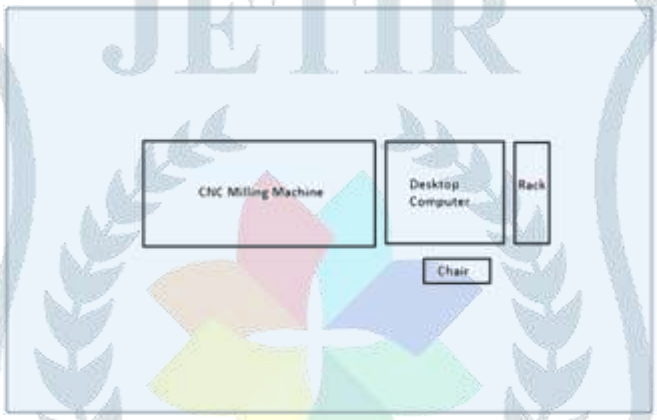

Figure 1. Schematic diagram of the experimental set-up employed in the experimental investigation undertaken in the present work

Figure 2 Experimental setup for sitting posture

Figure 3 Experimental setup for standing posture

B: General Experimental Procedure

Before starting the experiment, the subject was given sufficient instructions to perform the job. A work piece of dimension 100mm x 100mm x 12mm aluminum flat was selected. The profile cutting operation (Fig. 4) was performed on a CNC milling machine for energy expenditure measurements. The activities, program entering and simulation, loading the work piece on the CNC milling machine, the execution of the CNC milling program, unloading the work piece, cleaning the machine and switching off the computer and machine were recorded through a Sony HD video camera. The job work was divided into 5 tasks and each task was further divided into elements. Task 1 consists of ten elements, Task 2 consists of eight elements, Task 3 consists of three elements, Task 4 consists of five elements, and Task 5 consists of seven elements. The energy expenditure for various tasks is determined using energy expenditure (EEP) software. A detailed report was generated using the EEP program after the recorded data input. The summary of the report generated is presented in Table 2. Figure 4 shows the work piece geometry (2D) for measurement of energy expenditures. Figure 5 shows 3D view of the work piece. Table 1., shows the CNC coded program for various operations performed on the CNC milling machine**.**

3. RESULTS AND DISCUSSION

An overview of the literature pertaining to studies on human performance using energy expenditure in the context of CNC milling environment indicated that either no or little consideration has been given to this area in researches conducted previously. On the other hand, the use of CNC machines all over the world is increasing day by day. Today a very large size of the workforce is associated with the work on CNC machine tools.

Figure 4 Work piece (2D) to be machined by the operator for energy expenditure measurements

Automated equipment has penetrated virtually every area of human life and work environments. Human-machine interaction is already playing a vital role across the entire production process, from planning individual links in the production chain right through to designing the finished product. Innovative technology is made for humans, used by and monitored by humans. The products, therefore, should be reliable in operation, safe, cost effective, accepted by personnel and last but not least, energy expenditure will be well within the permissible limit. This interplay between technology and user, known as human-machine interaction, is hence at the very heart of industrial automation, automated control, and industrial production. Keeping in view these considerations, the present study was designed to explore how energy expenditure can be determined in a CNC milling environment using *Energy Expenditure Prediction Program*. Further, the study also aimed at to compare the determined energy expenditure with standards set by various agencies.

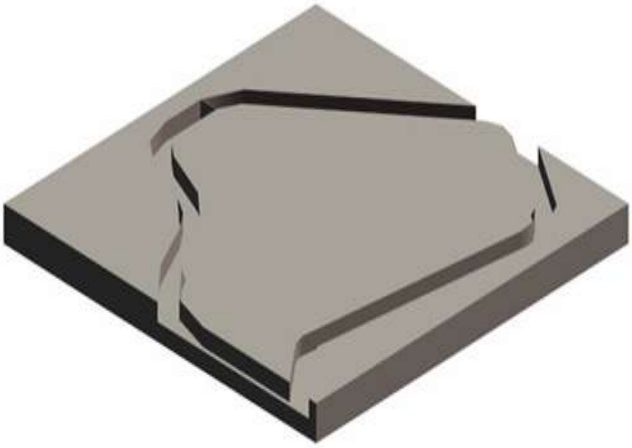

Figure 5 Work piece (3D) machined for energy expenditure measurements

Table 1. CNC coded program for machining the work piece

PROGRAM	DESCRIPTION
N5 G00 G54 G64 G90 G17 X-20 Y-20 Z50	All axes are in home position
N10 S450 M03 F250 D01 (12.5 MM DIA)	Spindle rotation at 450 rpm
N15 C0	Retraction plane
N20 Z5	Z axis move in rapid and stop 5mm away from working position X-20 and Y-20
N25 G01 Z0	Z axis move in feed rate at Z position 0.0 mm X-20 and Y-20
N30 Z-5	Z axis move in feed rate at Z-5mm
N35 G42 X0 Y0	Axis move rapidly at X0 and Y0 position
N40 X10 Y10 U4	Axis move rapidly at X10 and Y10 position of having radius 4mm
N45 X80 Y0 U8	X axis move 0 mm and Y axis move 0mm having radius 8mm
N50 X100 Y20 U8	X axis move 100mm and Y axis move 20mm with radius 8mm
N55 X60 Y80 U7	X axis move 60mm and Y axis move 80mm with radius 7mm
N60 X40 Y80 U7	X axis move 40mm and Y axis move 80mm with radius 7mm
N65 X30 Y55 U8	X axis move 30mm and Y axis move 55mm with radius 8mm
N70 X0 Y40 U20	X axis move 0mm and Y axis move 40mm with radius 20mm
N80 X0 Y0	X axis and Y axis both return at zero position
N85 G40 X-20 Y-20	All axis return at home position X-20 and Y-20
N90 G00 Z50	Z axis move in rapid mode 50mm away from work piece surface
N95 Y100	Y axis move 100mm in rapid mode
N100 M30	Program stop and rewind

Table 2., indicates the energy expenditure measurements for various tasks, namely CNC milling machine ready for operation, penal program entry, simulation, movement from rack to machine and loading work piece, tool setting, program execution, unloading work piece and movement from machine to rack and machine switch off. The Table 2., also indicates the rate and energy expenditures in discrete production environment during, program entering and simulation and CNC machine ready for operation as 2.26 kcal/min and 33.92 kcal respectively, loading the work piece on the CNC milling machine, 2.34 kcal/min and 35.08 kcal respectively, execution of CNC milling program, 5.67 kcal/min and 319.51 kcal respectively, unloading the work piece, 2.46 kcal/min and 9.27 kcal respectively, cleaning the machine and switching off the computer and machine, 2.46 kcal/min and 4.86 kcal respectively, The total energy expenditure for complete job is determined as 402.64 kcal and the job energy rate as 4.36 kcal/min.

Table 2. Energy expenditure measurements through energy expenditure prediction program for work piece

NAME Task Title	Elements	Cycle Duration (min)	Task Duration (hr.)	Total Posture Energy (Kcal)	Total Elements Energy (Kcal)	Cycle Energy (Kcal/cycle)	Task Energy Rate (Kcal/min.)	Total Task Energy (Kcal)
Task 1	10	15	0.25	31.5	2.42	33.92	2.26	33.92
Task 2	8	15	0.25	32.7	2.38	35.08	2.34	35.08
Task 3	3	2	0.94	4.2	7.13	11.33	5.67	319.51
Task 4	5	2	0.066	4.36	0.32	4.68	2.34	9.27
Task 5	7	3	0.033	6.54	0.83	7.37	2.46	4.86

Task Portfolio

Job Duration:	1.539 hours
No. of Tasks:	5
Job Energy:	402.64 Kcal
Job Energy Rate:	4.36 Kcal/min

Task Title	Description
Task 1	PROGRAM ENTERING AND SIMULATION
Task 2	LOADING THE WORKPIECE ON THE CNC MILLING MACHINE
Task 3	EXECUTION OF CNC MILLING PROGRAM
Task 4	UNLOADING THE WORKPIECE
Task 5	CLEANING THE MACHINE AND SWITCHING OFF THE COMPUTER AND MACHINE

The Table 3., shows a human-CNC machine interaction chart. The chart indicates the working time percentage of human as 94.65% and idle time percentage as 5.35%. Also the chart indicates the CNC machine working percentage as 8.01% and idle time percentage as 91.99% and computer working percentage as 97.34% and idle time percentage 2.66%.

Table 3. Human-Computer-CNC Milling machine chart

HUMAN MACHINE INTERACTION CHART
(Work piece for machining on CNC Milling Machine)

S.NO.	TASK	TIME (S)	HUMAN	COMPUTER	MACHINE
1	PROGRAM ENTERING AND SIMULATION	29760	29760	29760	
2	LOADING THE WORKPIECE ON THE CNC MILLING MACHINE	666	666		666
3	EXECUTION OF CNC MILLING PROGRAM	1732		1732	1732
4	UNLOADING THE WORKPIECE	61	61		61
5	CLEANING THE MACHINE AND SWITCHING OFF THE COMPUTER AND MACHINE	133	133		133
	TOTAL TIME	32352	30620	31492	2592

HUMAN MACHINE INTERACTION CHART
CYCLE TIME=32352 S

TIME (S)	HUMAN	COMPUTER	MACHINE
WORKING	94.65	97.34	8.01
IDLE	5.35	2.66	91.99

Furthermore, it is observed from the Fig. 6 that during tasks 1, 2, 4 and 5 the energy expenditure was below the standard levels, (Sanders and McCormick, 1992). Therefore, it can be said emphatically that during CNC milling operation the tasks 1, 2, 4 and 5 can be considered well ergonomically designed.

Figure 6 indicates that in case of task 3, the standard energy expenditure is high; therefore, it is explored that ergonomic studies should be conducted to design the better human-CNC milling machine interaction environment so as to reduce the energy expenditures during task 3.

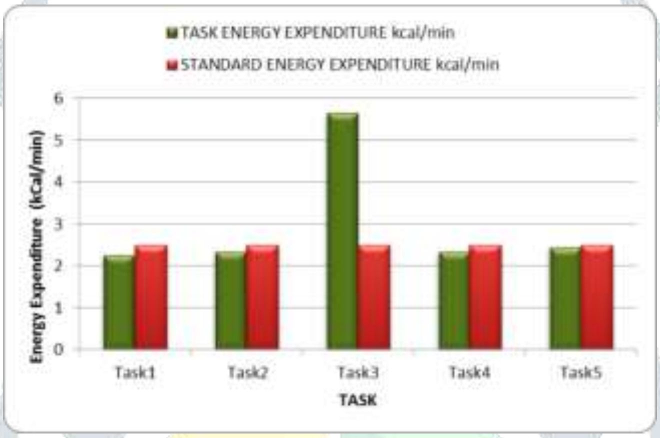

Figure 6. Comparison of measured and standard energy expenditure during tasks of the experiment

4. Conclusion

The World Health Organization (WHO) and the Occupational Safety and Health Administration (OSHA) consider work related energy expenditure to have multi-factorial causes. Management and workers in the current context of automation are greatly concerned with the working environment, ergonomics, the quality of work and occupational safety and health. Developments in information and communication technologies and specialized work requiring repetitive tasks have resulted in a need for human-machine interface design from energy expenditure point of view.

This study presented an effective approach for evaluation of a CNC milling environment using energy expenditure prediction program. For various tasks, a detailed report through software was generated for the analysis. On the basis of present study for discrete production environment, the following concluding remarks are drawn:

(i) The energy expenditure during CNC milling machine program entering and simulation operation determined through energy expenditure prediction program is 33.92 kcal. This energy is well within standard level (37.5 kcal), therefore, it is concluded that the concerned task is ergonomically designed.

(ii) The energy expenditure during loading the work piece on the CNC milling machine determined through energy expenditure prediction program is 35.08 kcal. This energy is below as compared to standard (37.5 kcal), therefore, it is concluded that the concerned task is ergonomically designed.

(iii) The energy expenditure during execution of CNC milling program is 319.51 kcal. This energy is above as compared to standard level (141 kcal), therefore, it is suggested that further ergonomic design of the above task in a CNC milling environment is required.

(iv) The energy expenditure during unloading the work piece from CNC milling machine is determined through energy expenditure prediction program is 9.27 kcal. This energy is below as compared to standard (9.9 kcal), therefore, it is concluded that the concerned task is ergonomically designed.

(v) The energy expenditure during cleaning the CNC milling machine and switching off the computer and CNC milling machine determined through energy expenditure prediction program is 4.86 kcal. This energy is below as compared to standard (4.95 kcal), therefore, it is concluded that the concerned task is ergonomically designed.

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