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Multi-Response Ergonomic Evaluation of Higher Age Group CNC Machine Operators

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Abstract
This work contributes to research on improving performance in a human-CNC machine interface (HCMI) environment. A salient contribution of this study is the use of a load cell to measure human performance. The developed novel system can measure cognitive and motor action responses simultaneously. The performance measurement system designed for this work may be used in other fields where systems are operated using control panels and for observing and evaluating the responses of mentally retarded persons (or persons with symptoms of Alzheimer's disease). The search time, motor action time and applied force were selected as response variables to accurately evaluate a computer numerically controlled (CNC) machine operator's performance. Based on a Taguchi experimental design, a full factorial design consisting of 27 (3^3) experiments was used to collect data on human performance. The collected data were analyzed using grey relational analysis, analysis of variance (ANOVA) and the F-test. ANOVA was performed using *Design-Expert software.* The designed research was shown to have a reasonable degree of validity via a *confirmation test.* This study represents an effective approach for the optimization of a higher age group operator-CNC machine interface environment with multi-performance characteristics based on a combination of the Taguchi method and grey relational analysis.
Relevance to industry: The findings of this work are directly applicable to the practical field to improve the design of a CNC-machines system. This work suggests that those responsible for the functioning and operation of CNC-machines workstations would have to redesign the system to reduce musculoskeletal injuries and other related problems. The present results can be quite useful for future system designers. It is emphasized that applying ergonomic principles to the design of CNC machines and interfaces can not only help to enhance machine performance and productivity but can also enable the human operator to feel comfortable and secure. As most companies have acquired automated manufacturing technology in recent years to be competitive, ergonomic and safety considerations are of the utmost importance.
Keywords: Multi-performance; Search time; Motor action time; Applied force; Load cell; CNC-Environment.

I. Introduction

This study determines the effect of anthropometric factors on performance in a human-CNC machine interface environment (HCMI). Historical evidence suggests that many manufacturing injuries are musculoskeletal disorders caused by cumulative trauma. Such injuries from cumulative wear and tear are called cumulative trauma disorders (CTDs). Back injuries, tendinitis and carpal tunnel syndrome are examples of common CTDs. Work place risk factors for CTDs include repetitive motion, high forces, awkward postures and vibration exposure. Work-related musculoskeletal disorders (WMSDs) remain a widespread and growing concern in automated industries. It is estimated that over five million workers sustain overextension injuries per year. Ergonomic intervention can be used to design workplaces to prevent overextension in workers, resulting in a savings of billions in workers' compensation for the manufacturing industry.

The ergonomic design of a workstation depends on the nature of tasks to be completed, the preferred posture of the operator and the dynamics of the surrounding environment (King and Fries, 2009). The workstation design should account for the adjustability of the working platform, clearances under the work surface, the computer numerically controlled (CNC) machine panel and the display support surfaces. The effectiveness with which operators perform their tasks at consoles or instrument panels depends in part on how well the equipment is designed to minimize parallax in the viewing displays, to enable ready manipulation of the controls and to provide adequate space and support for the operator. In the past, studies were conducted on the operators' physical impairments that were caused by various factors related to machining operations. Discomfort was used to measure postural stresses(Kee and Lee, 2012).

Working posture has been considered by many researchers as a focus on human performance. Khan (2012), Khan and Asghar (2011) and Khan and

Asghar (2010) researches evaluated the effect of working postures on human performance in a computer numerically controlled-electro discharge machine (CNC-EDM) environment. Assessments of the performance indicated a significant effect of levels of angle of abduction and viewing angle. To eliminate discomfort and reduce injuries as far as musculoskeletal and other related problems are concerned, findings of these researches suggested that CNC-EDM system should be re-designed so as to achieve, a 45 degree angle of abduction and a 21 degree viewing angle.

Slowing of motor performance in human aging is a well demonstrated clinical observation, both studied with simple and complex motor tasks (Jimenez-Jimenez et al., 2011; Ruff and Parker, 1993 and Shimoyama et al., 1990). Finger tapping (FT) frequency lowers with advancing age (Cousins et al., 1998; Elias et al., 1993 and Hermsdorfer et al., 1999). Aging seems to influence the performance of simple or complex reaction time tasks, including visual reaction time, being the response times longer in elderly people (Chen et al., 1994; Nissen and Corkin, 1985 and Pelosi and Blumhardt, 1999).

Research on age-related cognitive change traditionally focuses on either development or aging, where development ends with adulthood and aging begins around 55 years (Germine et al., 2011). The said approach ignores age-related changes during the 35 years in between, implying that this period is uninformative. Germine et al. (2011) investigated face recognition as an ability that may mature late relative to other abilities. The study using data from over sixty thousand participants, traced the ability to learn new faces from pre-adolescence through middle age. In three separate experiments, the finding show that faces learning ability improves until just after age 30- even though other putatively related abilities (inverted face recognition and name recognition) stop showing age-related improvements years earlier. The study data provide the behavioral evidence for late maturation of face processing and dissociation of face recognition from other abilities over time demonstrates that studies on adult age development can provide insight into the organization and development of cognitive systems.

Multiple causes contribute to the prolonged reaction-times (RT) observed in elderly persons (Bautmans et al., 2011). The involvement of antagonist muscle co-activation remains unclear. Bautmans et al. (2011) studied Mm. Biceps and Triceps Brachii activation in 64 apparently healthy elderly (80 ± 6 years) and 60 young (26 ± 3 years) subjects, during a simple RT-test (moving a finger using standardized elbow-extension from one push button to another following a visual stimulus). RT was divided in pre-movement-time (PMT, time for stimulus processing) and movement-time (MT, time for motor response completion). The study indicates that RT performance was significantly worse in elderly compared to young; the slowing was more pronounced for movement time than pre-movement time. Elderly subjects showed significantly higher antagonist muscle co-activation during the pre-movement time phase, which was significantly related to worse movement and reaction times (p□ 0.01). Also, during movement time phase, antagonist muscle co-activation was similar for both age groups. The study concluded that increased antagonist muscle co-activation in elderly persons occur in an early phase, already before the start of the movement. The findings provide further understanding of the underlying mechanisms of age-related slowing of *human motor performance*.

Chung et al. (2010) investigated the effect of age and two keypad types (physical keypad and touch screen) on the usability of numeric entry tasks. Twenty four subjects (12 young adults 23-33 years old and 12 older adults 65-76 years old) performed three types of entry tasks. Chung et al. (2010) noticed that the mean entry time per unit stroke of the young adults was significantly smaller than that of the older adults. The older adults had significantly different mean entry times per unit stroke on the two keypad types. Also, the error rates between young and old adults were significantly different for the touch screen keypad. The subjective ratings showed that the participants preferred the touch-screen keypad to the physical keypad. The results of the study showed that the older adults preferred the touch-screen keypad and could operate more quickly, and that tactile feedback is needed for the touch-screen keypad to increase input accuracy. *The study suggests that the results can be applied when designing different information technology products to input numbers using one hand.*

The use of computer controlled devices is constantly increasing. At the same time the population of the industrialized world is aging. Lindberg et al. (2006) investigated the speed with which users of different ages can find a specific computer icon from a group of others. The results show that *search performance* slows with age. However, individual variability in search performance was very high within all age groups. The study suggests that icon used in graphical user interfaces should be at least about 0.7 cm at a viewing distance of 40 cm, for the majority of users to be able to perform their computerized tasks with relative ease. Also, the study concluded that the inter-icon spacing should be moderate, preferably about the same as the icon size and ideally user interfaces should be adaptable to individual user needs and preferences.

Although connections between cognitive deficits and age-associated brain differences have been *elucidated, relationships with motor performance are less understood.* Seidler et al. (2010) review age-related brain differences and motor deficits in older adults in addition to cognition-action theories. Age related atrophy of the motor cortical regions and corpus callosum may precipitate or coincide with motor declines such as balance and gait deficits, coordination deficits and movement slowing. The study concluded that in general, older adults exhibit involvement of more widespread brain regions for motor control than young adults.

The population of the developed countries is becoming older while computer use is affecting increasingly wide aspect of life (Hawthorn, 2000). It is increasingly important that interface designs make software accessible to older adults. The study noticed that there is almost no research on what makes an interface usable for older adults. Hawthorn (2000) reviews the findings on the effects of age on relevant abilities and uses this information to provide suggestions to consider when designing interfaces for older users. *The study concludes with indications of the needed research in the area of interface design for older users.* Kang and Yoon (2008) observed the behavior of younger adults (20-29 years old) and middle-aged adults (46-59 years old) interacting with complicated electronic devices. The study examined various aspects of interaction behaviors in terms of performance, strategies, error consequences, physical operation methods and workload. The analysis of age-related differences included differences in background knowledge. The results revealed that differences in age meaningfully affected the observed error frequency, the number of interaction steps, the rigidity of exploration, the success of physical operation methods and subjective perception of temporal demand and performance. In contrast, trial-and-error behavior and frustration levels were influenced by background knowledge rather than age.

Designing human-machine interfaces that respect the ergonomic norms and following rigorous approaches constitute a major concern for automated systems designers. The increased need on easily accessible and usable interfaces leads researchers in this domain to create methods and models that make it possible to evaluate these interfaces in terms of utility and usability. Two different approaches are currently used to evaluate human-machine interfaces (Chikhaoui and Pigot, 2010), empirical approaches that require user involvement in the interface development process and analytical approaches that do not associate the user during the interface development process. This work presents studies of user performance on three principal tasks (cognitive, motor action and applied force) of the machine panel interface, developed in the context of CNC machine system. Chikhaoui and Pigot (2010) investigated that cognitive models show better accuracy of the user performance. In order to provide a comfortable environment, attention should be brought to ensure that people should easily access and manage the information in the environment. This can be reached by providing the user an interface that is accessible, usable and efficient (Joon et al., 2007). Each human-machine interface must be clear enough, to reduce the cognitive effort and allowing a good interaction with the environment. Therefore, the evaluation of human-machine interfaces appears a significant contribution in the design of applications and systems dedicated for automated machines.

The literature review indicates the need of separate interface designs for higher age group individuals. It is also observed that the cognitive and motor performances of peoples vary with the age. Hence there is a need to take up more studies in order to dig deeply into the insight of the phenomena of human aging. However, further research is needed in manufacturing environment, to draw guidelines for the HCMI designers as to what level of anthropometric parameters will be really required to enhance the higher age group operator performance. It is noticed that almost all researchers have strongly stressed on musculoskeletal disorders as the major source for human performance decrement. The present study considers the impact on performance in a human-CNC machine interface (HCMI) environment. Three response variables are selected for this work. First the search time, second the motor action time and third the applied force. Anthropometric factors in the present study are incorporated in terms of variability considered in CNC machine working environment. Keeping in view the above research work with respect to musculoskeletal disorders and anthropometric factors, three factors are selected for this work. First the CNC machine panel height, second the panel angle and third the working distance. The domain needs to enrich more for the benefit of the researchers and practitioners.

II. Methods

2.1. Problem statement

The preceding discussion shows that the effects of anthropometric considerations, such as machine panel height, panel angle and working distance, on higher age group operator performance, particularly in the context of HCMI, are still not fully understood; thus, a wide scope exists for investigating these effects. The research problem for the present work was formulated accordingly.

There has been a rapid growth in the use of CNC machines. These machines have entered virtually every area of our life and work environments. As CNC machine applications have become more widespread globally, the musculoskeletal problems associated with these machines have also generated more concern. Automated technologies are becoming increasingly popular. However, the pace of research in the field of HCMI environment has been rather slow in comparison to the growth rate of CNC machines, not only in developed nations but also in developing countries, such as India. The human problems associated with the HCMI environment are a major research area, in which the extent and rate of success are determined within a framework of effective and fruitful use of current automated technologies. There is a dire need for making automated machine systems more useful, easier-to-use, faster, more efficient and more compatible with operation from an *ergonomics* point of view, thereby catering to the demands of designers, manufacturers, purchasers and users. The literature survey indicated that most previous researchers have mainly emphasized the need to design and develop varieties of automated machine systems.

The present work was designed against this background to resolve various basic issues in the use of CNC machine tools. The experiments investigated higher age group male performance for CNC machine tools as a function of the machine panel height, the panel angle and the working distance. The present study investigated the effects of an *older* group, aged *42-46* years, for *male operator* performance on a CNC machine tool.

2.2. Experimental design

In this study, human performance was measured in terms of the search time, the motor action time and the applied force on the CNC machine panel keys. The search time, motor action time and applied force features were selected based on previous research (Bedny and Karwowski, 2006; Bergmann et al., 2011; Bothell, 2004; Chen and Chiang, 2011 and Layer et al., 2009). Before the actual experimental work, a pilot study was conducted to determine the discrete levels of three HCMI parameters that could enable the efficient and comfortable operation of a CNC machine tool. The factors and their levels that were selected for experimental investigation are described as follows. Three variables were considered in the study, i.e., the CNC machine panel height (Parameter A) at three levels, “90 cm”, “110 cm”, and “130 cm” (Sanders and McCormick, 1992); the CNC machine panel angle (Parameter B) at three levels, “30 degrees”, “60 degrees” and “90 degrees”; and the working distance (Parameter C) at three levels, “10 cm”, “20 cm” and “30 cm” (Chikhaoui and Pigot, 2010). The HCMI parameters/ design factors and their values at different levels are listed in Table 1.

Table 1 : Levels of variables used in the experiments

Factor ident-ifier	Factor	Unit	Level 1	Level 2	Level 3
A	CNC machine panel height	cm	90	110	130
B	CNC machine panel angle	deg-rees	30	60	90
C	Working distance	cm	10	20	30

The experiments were conducted using a *Taguchi experimental design* for which an *appropriate orthogonal array (OA)* was selected. An OA was selected for the experiments by first computing the total number of degrees of freedom (df). For example, a *three-level* design parameter corresponds to *two* degrees of freedom. The degrees of freedom associated with the *interaction* between two design parameters are given by the *product* of the degrees of freedom of the two respective design parameters. In the present study, there were *eighteen (2+2+2+4+4+4)* degrees of freedom because there were three HCMI design parameters (A, B and C) with three levels each and three two-way interactions, AxB, AxC and BxC. Once the required degrees of freedom were known, the next step was to select an appropriate OA for the specific task. The degrees of freedom for the OA needed to be greater than or at least equal to those for the design parameters (Goel et al., 2011). A L_{27} OA with 27 rows (corresponding to the number of experiments) was chosen for the investigations. The L_{27} (3^{13}) array was an OA of 27 distinct rows, which provided 26 degrees of freedom for studying different effects. This design matrix can be used to examine a maximum of 26/2 = 13 two-df effects. Thus, the L_{27} can be used to accommodate a full 3^3 factorial design. The three parameters (A, B and C) and the three two-way interactions (AxB, AxC and BxC) needed 18 degrees of freedom and occupied 18/2 = 9 of the 13 columns of an L_{27} OA. The remaining four columns of the L_{27} OA were treated as dummy parameters.

The search time, the motor action time and the applied force were selected as response variables for evaluating a CNC machine operator’s performance. A full factorial design (based on a L_{27} OA) consisting of 27 (3^3) experiments was used to collect human performance data in terms of the search time, the motor action time and the applied force. The collected data were analyzed using grey relational analysis, analysis of variance (ANOVA) and the F-test. These methods are described below.

2.2.1. Grey relational analysis

The grey relational grade is an index that represents multiple performance characteristics. The index describes the relationships among a series of experimental results. The grey relational grade is determined by pre-processing the experimental data to transfer the original sequence to a comparable sequence. In grey relational analysis, the grey relational grade indicates the relationship among the sequences. If two sequences are identical, then the grey relational grade equals '1'. The grey relational grade also indicates the degree of influence that the comparability sequence can exert over the reference sequence. Therefore, if a particular comparability sequence is more important than another comparability sequence relative to the reference sequence, the grey relational grade for that comparability sequence and reference sequence will be higher than the other grey relational grade (Khan et al., 2010, Ross, 1988, Siddiquee et al., 2010 and Yang et al., 2006). In this work, the comparability sequence and the reference sequence are treated as being equally important.

2.2.2. Analysis of variance (ANOVA) and F-test

ANOVA and the F-test determine the individual factors and the interaction between these factors that significantly affects multi-performance characteristics. This statistical analysis is based on the variance, the degrees of freedom, and the sum of squares, the mean square, the F-ratio, the P-value and the % age contribution to the total variation (Ma et al., 2007). The detailed procedure for calculating parameters pertaining to ANOVA is described in (Samant et al., 2008). In this work, ANOVA, interaction effect analysis and various model adequacy tests were carried out using *Design Expert Software* (2012).

2.3. Subjects

A pool of 27 potential subjects was selected for the present work. This pool included older males ranging from 42 years to 46 years in age. The selected subjects were employees of the AMU, Aligarh, India. A self-designed questionnaire was used to select the subjects. Out of the 130 questionnaires distributed among employees, 101 responded, out of which 27 older males were selected on the basis of well-defined anthropometric characteristics. The selected subjects also expressed their willingness to participate in the present study. No subject participated in more than one experiment.

2.4. Stimuli and the experimental task

Stimuli were presented to the subjects as colored light emitting diodes (LEDs) that were fixed on an adjustable height display board. The colors used for the visual stimuli were *red, blue, yellow, white and green.* The visual stimuli were provided during the respective tasks by the experimenter controlling the 'on' and 'off' positions of the LEDs. The LEDs were connected to one of the channels (Channel-2) of the oscilloscope through a switchboard. An indigenously designed CNC machine panel and working platform were used for all the studies. The panel was fitted with *'load cells'* (piezo-electric sensors), and the assembly was fixed onto an adjustable 'height' and 'angle' platform (Sanders and McCormick, 1992). Variable working distances (Chikhaoui and Pigot, 2010) were realized by pasting colored strips on the ground in front of the assembled platform. The machine panel had two lead connections. The first connection was with one of the channels (Channel-1) of the oscilloscope and the second connection was with the visual display unit (VDU) monitor through the central processing unit (CPU). During the experiments, the subjects stood, according to the combination of selected HCMI parameters, in front of the working platform (Maldonado-Macias et al., 2009) with the index finger of the right hand (which was used to record the search time) placed on the CNC machine panel 15 cm away (Chikhaoui and Pigot, 2010) from the panel keys (which were used to record the motor action time and the applied force). The subject's left hand remained free along the subject's side. The subjects were required to respond to a visual signal (a LED of a particular color that was switched on for a short period) that was provided by the experimenter through the switchboard. The signal at the moment of 'LED-ON' was recorded by the oscilloscope. The subjects were asked to search the CNC machine panel for the key, which was similar to the first *alphabet* of the activated color stimuli (i.e., for the color *Green*, the first alphabet was 'G'), without lifting their right-hand index finger. As soon as the required '*key'* was '*searched'*, the subject lifted her index finger and depressed the key. The signal at the moment of the *'finger-lift'* was recorded by the oscilloscope. The time difference, in milliseconds, between the visual-stimuli and the finger-lift was saved as the *'search time'* (the cognitive time). To ensure correct task execution (matching 'key search and press' with the supplied visual signal), *software* in the *C++* language was developed, which also helped to achieve *'zero error'* experimental results. The software was loaded onto a computer system that was connected to a self-designed CNC machine panel assembly. As a particular alphabet key (out of only five possible alphabet keys R, B, Y, W and G) was depressed on the machine panel (in response to a visual signal), the loaded software displayed a full VDU screen image (of a square shape) of the color whose first alphabet was pressed (i.e., if the subject depressed 'R', the software displayed a full VDU screen square 'RED' shaded image). This ultimately ensured correct task execution. When the task was incorrectly executed, the task was repeated in a random order. The software did not display an image if a key other than one of the five previously mentioned alphabets was depressed. Two more signals at the moment of *'searched key pressing'* were recorded, the first on the x-axis of the oscilloscope and the second on the y-axis. On the x-axis, the time difference, in milliseconds, between the 'finger-lift' and the 'searched key press' moments was saved as the *'motor action time'*. When the searched key was depressed, the *'applied force'* on the panel key was recorded in millivolts on the y-axis of the oscilloscope. Each subject executed the same task for five randomly-supplied visual stimuli (Red, Blue, Yellow, White and Green). The same experiment was conducted for all the participants. Finally, the average of five human performances, for the *'search time',* the *'motor action time'* and the *'applied force'*, was recorded for analysis. For *experimental validation*, a movie of each subject was also recorded by a video camera (SONY Digital Handycam; HDR-XR500: 12 mega pixels). The video camera was used to record and photograph the subject to identify stress in full-body postures during CNC machine operation (Maldonado-Macias et al., 2009).

2.5. Experimental set-up

In this research, a working platform was designed using a load cell (piezo-electric sensor) combination, which was fixed to a conventional computer keyboard. This structure was then assembled with a self-fabricated adjustable (in terms of the height and angle) panel to resemble the shape of a CNC machine panel.

Human performance was measured in terms of search time, motor action time and applied force on the machine panel keys. All experiments were performed in a simulated environment chamber of 5.2 m x 4.4 m x 2.9 m size, specifically developed within the premises of the Department of Mechanical Engineering, AMU, Aligarh, India. The *temperature* of the experiment chamber (Sanders and McCormick, 1992) was approximately 23 ± 2 degree Celsius measured through wall temperature indicator (model: me DTI 4001). *Reflection* of the light from windows and door was eliminated through proper covering. When the chamber was closed, the cubicle got *acoustically sealed* from the outside environment. The *illumination* level throughout all the experimental sessions (OSHA, 2011 and Sanders and McCormic, 1992) was maintained at 590 ± 10 lux. This level of luminance was monitored through a digital lux meter (model: LT Lutron LX-101). The relative *humidity* level of the experiment chamber (Sanders and McCormic, 1992) was approximately 77 ± 3 percent measured through 'hair hygrometer' (model: Ekbote HAIR Hygrometer). *Sound* level throughout all the experimental sessions (OSHA, 2011 and Sanders and McCormic, 1992) was approximately 52 ± 3 dBA measured through sound level meter (model: LT Lutron SL-4001). Measuring tape, digital vernier caliper and weighing machine were used to measure various anthropometric characteristics of the subjects. The *search time*, *motor action time* and *applied force* was measured through 2-Channel Oscilloscope (model: DS 1062 C; make: Rigol Digital Oscilloscope Ultrazoom; specification: 60 MHz 400 MSa/s).

The positions of the indigenously designed CNC machine panel, the subject and other peripheral devices were maintained as portrayed in the schematic (Figure 1).

Figures 1 and 2 show that the standing subject (item 1 of Figure 1) in front of CNC machine panel could maintain three working distances (10/20/30 cm), as set by the colored strips.

The working platform (item 2 of Figure 1) could be adjusted to any height (90/110/130 cm or other heights) by using an adjustable screw, as depicted in Figure 3.

The CNC machine panel (item 2 of Figure 1) could also be adjusted to any angle (30/60/90 degrees or other angles) via the adjustable mechanism shown in Figure 4.

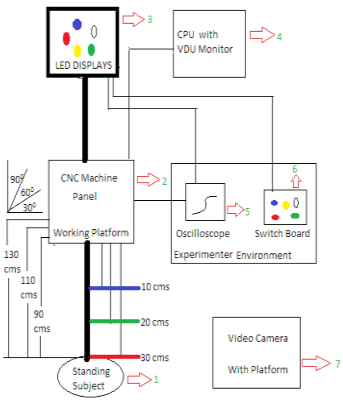

Figure 1: Schematic of the experimental set-up used in the present work

Figure 2: Working distances shown with colored strips

Figure 3: CNC machine panel height adjustment system

Figure 4: CNC machine panel angle adjustment mechanism

The colored visual stimuli were provided by item 3 in Figure 1. Figure 5 shows how the colored LED board was used to provide a variable height visual signal.

Figure 5: Variable height colored LED board

Item 4 in Figure 1 indicates where the CPU and a VDU monitor were stationed to ensure that the experimental task was correctly executed. Figure 6 shows the CPU and the VDU monitor displaying a green square image when a subject depressed alphabet ‘G’ on the CNC machine panel in response to an activated green LED visual signal.

Figure 6: Full VDU green-colored screen square in response to an applied green visual stimulus

Items 5 and 6 of Figure 1 show the experimenter environment with a 2-Channel oscilloscope for recording human performance and a switch board for providing visual stimuli, respectively. Figure 7 depicts the positions of the oscilloscope and the switch board.

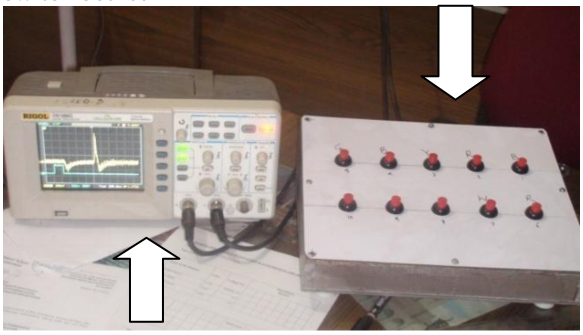

Figure 7: Oscilloscope and switch board positions

Item 7 in Figure 1 shows the location where the subjects were filmed while they performed the task. Figure 8 indicates the position of a SONY Digital Handycam video camera.

Figure 8: Photograph of the stand used to hold the camera fixed

Figure 9 shows a subject with his index finger placed at a position on the panel. As the subject lifted his finger, a search time signal was recorded by the oscilloscope.

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Figure 9 : Subject waiting for visual stimuli

Figure 10 depicts the same subject performing a motor action in response to a supplied visual stimulus. The corresponding motor action time and applied force signals were recorded by the oscilloscope.

Figure 10 : Subject performing motor action

Figure 11 shows the arrangement of the load cells (piezo-electric sensors) that were fixed to a keyboard. This structure was assembled with a self-fabricated adjustable panel to resemble the shape of a CNC machine panel.

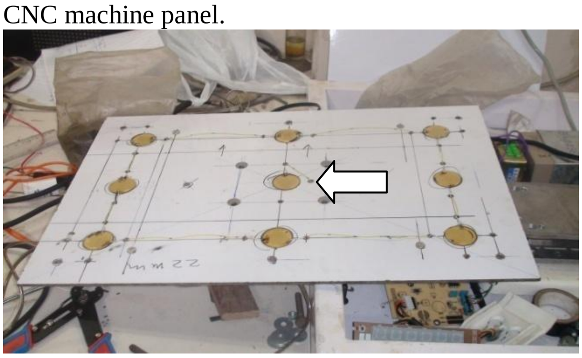

Figure 11: Load cells (piezo-electric sensors) fixed on a mica-sheet

2.6. General experimental procedure

A pilot study was performed in advance of the actual experiments. This study helped to pre-plan the details of the experimental sessions and check the suitability of the observation sheet for collecting experimental data. In the study, a sample of 27 older male subjects, who all fulfilled the pre-specified anthropometric characteristics, was selected from the pool of potential subjects. The following preparatory steps were undertaken before conducting the experiments:

(i) each subject that was selected for the task was briefed on the experimental objective and

(ii) a training session familiarized each subject with the designed CNC machine panel; trial experimental runs were conducted for training purposes.

The subject stood in front of the machine panel, according to the selected HCMI parameters, and was given instructions; the subject then performed the steps given below, in the prescribed order, for both the training and the actual experimental sessions.

(a) The subject was required to keep his right-hand index finger on a pre-defined position on the machine panel.

(b) Colored visual stimuli were randomly presented to the subject by the experimenter, through the switchboard, during different sessions.

(c) The subject responded by lifting the same index finger and depressing the requisite key on the CNC machine panel; the task was repeated five (for red, blue, yellow, white and green visual signals) times for each subject.

(d) The human performance, in terms of the search time, the motor action time and the applied force on the key of the machine panel, was recorded by the oscilloscope for each visual signal (Figure 12).

(e) The average of five performances was analyzed.

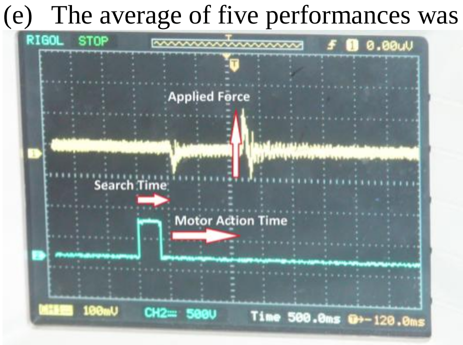

Figure 12: Recording of the search time, the motor action time and the applied force by a 2-channel oscilloscope

The parameters that most affected performance in the human-CNC machine interface environment were identified. These parameters were the CNC machine panel height, the panel angle and the working distance. A realistic human performance measure system was then developed. The older male performance was measured in terms of the search time, the motor action time and the applied force on the panel keys. Grey relational analysis and analysis of variance techniques were found to be suitable for a study of this nature, which involved many variables that possessed multi-performance characteristics and interacted with each other in a complex manner.

III. Results

3.1. Comprehension

A literature review on human performance in an HCMI environment indicated that little or no research has been performed in the area, particularly on older male operators. In contrast, CNC machines are increasingly used all over the world. Today, a very large workforce uses CNC machine tools. Keeping these considerations in mind, the present study explored how the performance of older age group male operators was affected by changing the machine panel height, the panel angle and the working distance, while working on the CNC machine tools in an HCMI environment. The study also determined the optimum machine panel height, panel angle and working distance to obtain optimal multi-performance characteristics.

To state these objectives in *statistical terms*, the following *null hypothesis* was constructed: ***"Varying levels of CNC machine panel height, panel angle and working distance impose equal magnitude of operational loading on higher age group operators resulting in no difference in human performance".***

3.2. The Experiment

Twenty-seven males, in the age group of 42-46 years, were selected from a pool of subjects to participate in the study. All the subjects had normal vision without corrective lenses. The chosen subjects were right-motor sided (right-handed). None of the subjects had a prior history of a neuromuscular disorder.

The procedure detailed in section 2.6 was followed for conducting the experiment and measuring the response variables of the search time, the motor action time and the applied force. All the experimental sessions were conducted between 10.00 hours and 14.00 hours to exclude temporal effects from the outcomes.

3.3. Data analysis of experimental results

The subjects committed no errors in performing the experimental task. This was ensured by a program that was developed in the C++ language. The human performance in terms of the *search time*, the *motor action time* and the *applied force* for different combinations of the panel height, the panel angle and the working distance for 27 experimental runs are listed in Table 2.

The following sequential steps were used to determine the optimal combination of the human-CNC machine interface parameters for multi-performance characteristics based on a grey relational analysis:

i) the S/N ratios for the experimental data were calculated,
ii) the S/N ratios were normalized,
iii) the corresponding grey relational coefficients were determined,
iv) the grey relational grades were calculated,
v) ANOVA was carried out to determine the significant contribution of the factors and
vi) a confirmation test was performed to check the validity of the results.

3.3.1 Optimal parameter combination

In the HCMI environment, lower values of the search time, the motor action time and the applied force indicate better performance. The S/N ratios of the search time, the motor action time and the applied force for the 27 experimental runs were calculated and are listed in Table 3.

Table 4 lists all the sequences following data pre-processing of the search time, the motor action time and the applied force. The deviation sequences Δ_{0i}, $\Delta_{max}(k)$ and $\Delta_{min}(k)$ for i=1-27 and k=1-3 were calculated.

The results for all the Δ_{0i} for i=1-27 are given in Table 5.

Using Table 5, Δ_{max} and Δ_{min} were determined to have the following values:

$\Delta_{max} = \Delta_{01}(1) = \Delta_{01}(2) = \Delta_{03}(3) = 1.000$

$\Delta_{min} = \Delta_{02}(1) = \Delta_{21}(2) = \Delta_{08}(3) = 0.000$

Table 6 lists the grey relational coefficient and grade for each experiment of the L_{27} OA.

Table 2 : Experimental design using the L_{27} orthogonal array

Experiment No.	A	B	C	Search Time in millise-conds	Motor action time in millise-conds	Applied force in millivo-lts
1	1	1	1	450	700	100
2	1	2	2	1000	1600	110
3	1	3	3	1000	1650	100
4	2	1	1	950	700	140
5	2	2	2	700	1300	120
6	2	3	3	950	1700	160
7	3	1	1	550	1370	170
8	3	2	2	500	700	220
9	3	3	3	650	800	200
10	1	1	2	700	1120	60
11	1	2	3	800	1600	130
12	1	3	1	800	1600	120
13	2	1	2	840	700	90

14	2	2	3	800	1350	150
15	2	3	1	780	1350	150
16	3	1	2	700	1200	105
17	3	2	3	720	1600	130
18	3	3	1	650	1150	160
19	1	1	3	740	700	100
20	1	2	1	850	1650	60
21	1	3	2	850	1850	120
22	2	1	3	850	1600	100
23	2	2	1	850	1600	120
24	2	3	2	1000	800	90
25	3	1	3	640	1200	150
26	3	2	1	950	1400	125
27	3	3	2	500	1050	110

Table 3 : S/N ratios

Exp-erim-ent No.	A	B	C	Search time S/N ratio (dB)	Motor action time S/N ratio (dB)	Appli-ed force S/N ratio (dB)
1	1	1	1	-53.064	-56.902	-40.000
2	1	2	2	-60.000	-64.082	-40.828
3	1	3	3	-60.000	-64.350	-40.000
4	2	1	1	-59.554	-56.902	-42.923
5	2	2	2	-56.902	-62.279	-41.584
6	2	3	3	-59.554	-64.609	-44.082
7	3	1	1	-54.807	-62.734	-44.609
8	3	2	2	-53.979	-56.902	-46.848
9	3	3	3	-56.258	-58.062	-46.021
10	1	1	2	-56.902	-60.984	-35.563
11	1	2	3	-58.062	-64.082	-42.279
12	1	3	1	-58.062	-64.082	-41.584
13	2	1	2	-58.486	-56.902	-39.085
14	2	2	3	-58.062	-62.607	-43.522
15	2	3	1	-57.842	-62.607	-43.522
16	3	1	2	-56.902	-61.584	-40.424
17	3	2	3	-57.147	-64.082	-42.279
18	3	3	1	-56.258	-61.214	-44.082
19	1	1	3	-57.385	-56.902	-40.000
20	1	2	1	-58.588	-64.350	-35.563
21	1	3	2	-58.588	-65.343	-41.584
22	2	1	3	-58.588	-64.082	-40.000
23	2	2	1	-58.588	-64.082	-41.584
24	2	3	2	-60.000	-58.062	-39.085
25	3	1	3	-56.124	-61.584	-43.522
26	3	2	1	-59.554	-62.923	-41.938
27	3	3	2	-53.979	-60.424	-40.828

Table 4: Sequence of each performance characteristic after data preprocessing

Experiment No.	Search time	Motor action time	Applied force
Reference sequence ⟶	1.000	1.000	1.000
1	0.000	0.000	0.393
2	1.000	0.851	0.467
3	1.000	0.966	0.000
4	0.936	0.000	0.652
5	0.553	0.637	0.533
6	0.936	0.913	0.755
7	0.251	0.691	0.802
8	0.132	0.000	1.000
9	0.461	0.137	0.927
10	0.553	0.484	0.000
11	0.721	0.851	0.595
12	0.721	0.851	0.533
13	0.782	0.000	0.312
14	0.721	0.676	0.705
15	0.689	0.676	0.705
16	0.553	0.555	0.431
17	0.589	0.851	0.595
18	0.461	0.511	0.755
19	0.623	0.000	0.393
20	0.796	0.882	0.000
21	0.796	1.000	0.533
22	0.796	0.851	0.393
23	0.796	0.851	0.533
24	1.000	0.137	0.312
25	0.441	0.555	0.705
26	0.936	0.713	0.565
27	0.132	0.417	0.467

Table 5 : Deviation sequences

Deviation sequences	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$	$\Delta_{0i}(3)$
Experiment no. 1	1.000	1.000	0.607
Experiment no. 2	0.000	0.149	0.533
Experiment no. 3	0.000	0.034	1.000

Experiment no. 4	0.064	1.000	0.348
Experiment no. 5	0.447	0.363	0.467
Experiment no. 6	0.064	0.087	0.245
Experiment no. 7	0.749	0.309	0.198
Experiment no. 8	0.868	1.000	0.000
Experiment no. 9	0.539	0.863	0.073
Experiment no. 10	0.447	0.516	1.000
Experiment no. 11	0.279	0.149	0.405
Experiment no. 12	0.279	0.149	0.467
Experiment no. 13	0.218	1.000	0.688
Experiment no. 14	0.279	0.324	0.295
Experiment no. 15	0.311	0.324	0.295
Experiment no. 16	0.447	0.445	0.569
Experiment no. 17	0.411	0.149	0.405
Experiment no. 18	0.539	0.489	0.245
Experiment no. 19	0.377	1.000	0.607
Experiment no. 20	0.204	0.118	1.000
Experiment no. 21	0.204	0.000	0.467
Experiment no. 22	0.204	0.149	0.607
Experiment no. 23	0.204	0.149	0.467
Experiment no. 24	0.000	0.863	0.688
Experiment no. 25	0.559	0.445	0.295
Experiment no. 26	0.064	0.287	0.435
Experiment no. 27	0.868	0.583	0.533

Table 6 : Calculated grey relational coefficient and grey relational grade and its orders for 27 comparability sequences

Experiment No.	Grey relational coefficient			Grey relational grade	Orders
	Search time	Motor action time	Applied force		
1	0.333	0.333	0.452	0.373	27
2	1.000	0.770	0.484	0.751	3
3	1.000	0.937	0.333	0.757	2
4	0.886	0.333	0.590	0.603	14
5	0.528	0.579	0.517	0.542	21
6	0.886	0.852	0.671	0.803	1
7	0.400	0.618	0.716	0.578	16
8	0.365	0.333	1.000	0.566	18
9	0.481	0.367	0.872	0.573	17
10	0.528	0.492	0.333	0.451	25
11	0.641	0.770	0.553	0.655	7
12	0.641	0.770	0.517	0.643	9
13	0.696	0.333	0.421	0.483	23
14	0.641	0.607	0.629	0.626	10
15	0.616	0.607	0.629	0.617	13
16	0.528	0.529	0.468	0.508	22
17	0.549	0.770	0.553	0.624	11
18	0.481	0.505	0.671	0.553	19
19	0.570	0.333	0.452	0.452	24
20	0.711	0.809	0.333	0.618	12
21	0.711	1.000	0.517	0.743	4
22	0.711	0.770	0.452	0.644	8
23	0.711	0.770	0.517	0.666	6
24	1.000	0.367	0.421	0.596	15
25	0.472	0.529	0.629	0.543	20
26	0.886	0.635	0.535	0.685	5
27	0.365	0.462	0.484	0.437	26

Figure 13 shows the change in the response on changing the factors from one level to the next. Table 6 clearly shows that for the experimental design conducted, the grey relational grade graph (Figure 13) for the older age operator-CNC machine interface parameters' setting of experiment number 06 had the highest value (0.803) of the grey relational grade. The sequence with the largest grey relational grade was closest to the quality characteristics desired. Additionally, the order of the grey relational grade for experiment number *'06'* is *'1'*. Thus, the parameter combination $A_2B_3C_3$ showed the best *performance* of all the three quality characteristics, i.e., the search time, the motor action time and the applied force.

The response table for the *Taguchi method* was used to calculate the average grey relational grade for each factor level. The procedure was to initially group the relational grades by the factor level of each column in the orthogonal array and to average the grades.

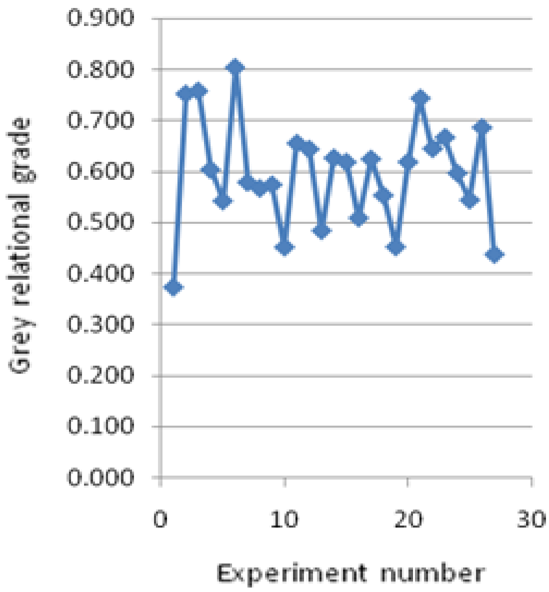

Figure 13 : Graph for the grey relational grade

For instance, the grey relational grades for factor A at level 1 and level 2 were determined as follows:

A_1=(0.373+0.751+0.757+0.451+0.655+0.643+0.452 +0.618+0.743)/9 = 0.605

A_2=(0.603+0.542+0.803+0.483+0.626+0.617+0.644 +0.666+0.596)/9 = 0.620

Using the same method, calculations were performed for each HCMI parameter level, and the response table was constructed as shown in Table 7. The grey relational grades represented the level of correlation between the reference and comparability sequences; a larger grey relational grade meant that the comparability sequence was more strongly correlated with the reference sequence.

Table 7 : Response table for grey relational grade

Symbol	Human-CNC Machine Interface (HCMI) Parameter	Level 1	Level 2	Level 3	Max - Min
A	CNC machine panel height	0.605	0.620	0.563	0.057
B	CNC machine panel angle	0.515	0.637	0.636	0.122
C	Working distance	0.593	0.564	0.631	0.067

Therefore, the comparability sequence had a larger value of the grey relational grade for the *search time*, the *motor action time* and the *applied force*. Based on this hypothesis, the level that provided the largest average response was selected in this study. The influence of each parameter level can be more clearly presented by means of a mean grey relational grade graph (a response graph). Figure 14 shows the response graph for the HCMI parameters and the mean value of the grey relational grade for different levels of each HCMI parameter.

The larger the grey relational grade, the better are the multi-performance characteristics. Higher values of the grey relational grade in Figure 14 indicate low search times, motor action times and applied forces. Table 7 and Figure 14 show that A_2, B_2 and C_3 corresponded to the largest value of the grey relational grade for the factors A, B and C, respectively. Therefore, $A_2B_2C_3$ was the optimal parameter combination condition for the multi-performance characteristics in an HCMI environment. In other words, a panel height of 110 cm, a panel angle of 60 degrees and a working distance of 30 cm was the optimal parameter combination condition for older age male operators working in the CNC machine environment. The parameter combination $A_2B_2C_3$ performed best in terms of all the three quality characteristics, i.e., the *search time*, the *motor action time* and the *applied force*. Comparing the entries in the last column of Table 7 shows that the largest difference between the maximum and minimum values of the grey relational grade were found for factor B, i.e., the CNC machine panel angle, followed by factor C, i.e., the working distance and then factor A, i.e. the CNC machine panel height. This observation indicates that the CNC machine *panel angle* had a stronger effect on the multi-performance characteristics than the CNC machine *panel height* and the *working distance*. The optimum working condition, which yielded the smallest search time, smallest motor action time and smallest applied force in the present study, was quite reasonable. For operators in the age group of 42-46 years, the optimum HCMI parameters combination emerged as $A_2B_2C_3$. At a 30-cm working distance the *shoulder abduction* was high. However, 110 cm CNC machine panel height and 60 degrees panel angle have resulted low *elbow* and *wrist abductions*. This parameter combination ultimately provides an overall less *musculoskeletal strain standing posture* for higher age group males. The $A_2B_2C_3$ combination resulted in the optimum performance of a CNC machine older age male operator because of a comfortable environment for search, motor action and force application.

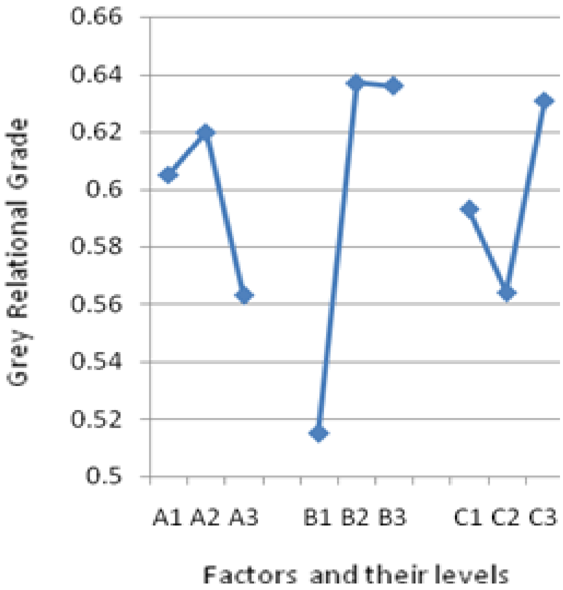

Figure 14 : Effect of HCMI parameter levels on multi-performance

Two-way interaction plots were obtained using *Design-Expert software(2012)* to estimate the parameter interaction effects. These plots were used to determine whether the interactions between the HCMI parameters significantly affected the multi-response characteristics, i.e., the grey relational grade. The graph for the interaction between factor A (the CNC machine panel height) and factor B (the CNC machine panel angle) is shown in Figure 15.

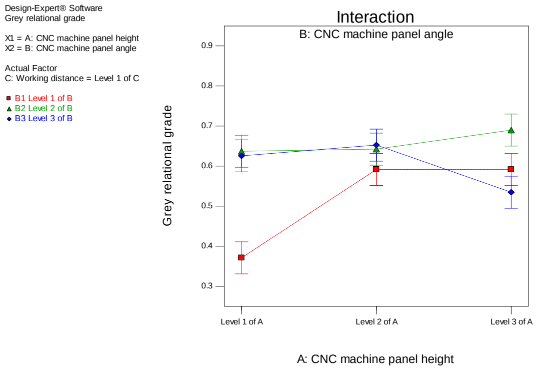

Figure 15 : Interaction plot for factor A and factor B

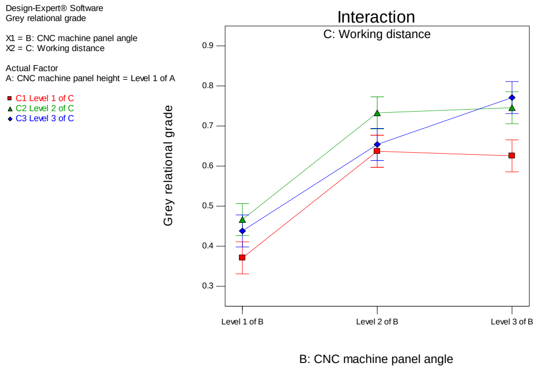

Figure 16 : Interaction plot for factor B and factor C

Figure 15 shows a strong interaction effect of the CNC machine panel height and the panel angle on the grey relational grade. Figure 15 indicates that when the CNC machine panel was operated at a 90-cm panel height, the multi-performance characteristic, i.e., the grey relational grade, was maximized at a 60-degree panel angle; the next highest grey relational grade values were for panel angles of 90 and 30 degrees, in that order. For a 110-cm panel height, the grade was maximized for a 90-degree panel angle, while the next highest grade value corresponded to a panel angle of 60 degrees, and the lowest grade value was found for a panel angle of 30 degrees. It is noteworthy that for a panel angle of 30 degrees, the grade increased when the machine operation shifted from a 90-cm to a 110-cm panel height, while a significant effect on the multi-performance characteristics was observed for changing operation from a 110- to a 130-cm panel height. Furthermore, for a 90 degree-panel angle, the grade continued to decrease as the machine operation was shifted from 90 to 110 cm and the machine panel height was shifted from 110 to 130 cm. The multi-performance characteristics of the HCMI environment were significantly affected by the panel height when the CNC machine was operated at a 60-degree panel angle.

The overall *minimum musculoskeletal strain posture* for higher age group male operators corresponded to a 130-cm CNC machine panel height, with the next lowest values corresponding to the 110-cm and 90-cm panel heights, in that order.

A graph showing the interaction between factor B (the CNC machine panel angle) and factor C (the working distance) is shown in Figure 16.

Figure 16 shows that the interaction between the CNC machine panel angle and the working distance had a strong effect on the grey relational grade. Figure 16 indicates that when the CNC machine was operated at a 30-degree panel angle, the multi-performance characteristic, i.e., grey relational grade, was maximized at a 20-cm working distance, followed by the 30-cm and 10-cm working distances. However, at the 90-degree panel angle, the grade was highest at a 30-cm working distance, followed by the 20-cm and 10-cm working distances. It is noteworthy that at working distances of 10,20 and 30 cm, the grade increased as the machine operation was transferred from a 30-degree to a 60-degree CNC machine panel angle. At a 30-cm working distance, a significant increase in grade was recorded. It should also be noted that the multi-performance characteristics of an HCMI environment at 10 and 20-cm working distances were marginally affected for higher age group male machine operators.

The *minimum musculoskeletal strain posture* for older males was concluded to correspond to a 60-degree CNC machine panel angle for 10 and 20-cm working distances and to a 90-degree panel angle for 30-cm working distance.

The graph for the interaction between factor A (the CNC machine panel height) and factor C (the working distance) is shown in Figure 17.

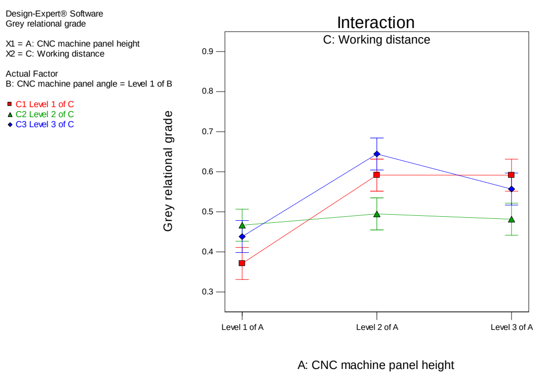

Figure 17 : Interaction plot for factor A and factor C

Figure 17 reveals that the interaction between CNC machine panel height and working distance has a strong effect on the grey relational grade. Figure 17 indicates when CNC machine is operated at 90 cm panel height, the multi-performance i.e. grey relational grade is the maximum at 20 cm working distance followed by 30 and 10 cm, respectively. The status of grade at 110 cm panel heights is that, it is highest at 30 cm working distance followed by 10 and 20 cm, respectively. However, at 130 cm panel height, the grey relational grade is the maximum at 10 cm working distance followed by 30 and 20 cm, respectively. It is significant to note that, at working distances 10 and 30 cm, the grade increases when CNC machine operation is shifted from 90 to 110 cm panel height. Furthermore, significant decrease in grade is observed at 30 cm working distances when CNC machine operation is shifted from 110 to 130 cm panel height. It is noteworthy that the multi-performance characteristics of HCMI are marginally affected by the panel heights when CNC machine is operated from a distance of 20 cm.The *minimum musculoskeletal strain posture* for higher age group males corresponded to a 110-cm CNC machine panel height for working distances 20 and 30 cm and to a 130-cm panel height for 10- cm working distance.
Figure 18 shows a three-dimensional (3D) view of the general factorial effects of the interaction between the CNC machine panel height and the panel angle. Lower human performance is observed if low wrist and elbow abductions are combined with low shoulder abduction. However, for moderate wrist abduction the overall muscular fatigue indicated was low. The Figure 18 precisely indicates that for higher age group males, the lowest performance emerged at CNC machine panel height 90 cm used with panel angle 30 degrees while as, highest performance is resulted at panel height 130 cm when combined with panel angle 60 degrees. Furthermore, higher

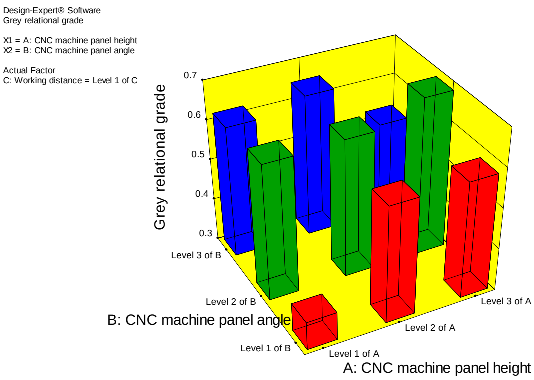

Figure 18 : General factorial effects of the interaction between the CNC machine panel height and the panel angle

moderate performance observed at CNC machine panel height and angle combinations of 110cm and 90 degrees, 110 cm and 60 degrees, 90 cm and 60 degrees and 90 cm and 90 degrees, respectively. However, lower moderate performance resulted at CNC machine panel height and angle combinations of 130 cm and 30 degrees, 130 cm and 90 degrees and 110 cm and 30 degrees, respectively. It can be concluded on the basis of 3D factorial effects that overall performance of higher age group males was better because of moderate wrist abduction at CNC machine panel angle 60 degrees irrespective of panel heights. Also, the overall performance was better due to moderate elbow abduction at CNC machine panel height 110 cm irrespective of panel angles. Figure 19 shows three-dimensional (3D) view of general factorial effects of interaction between CNC machine panel angle and working distance.

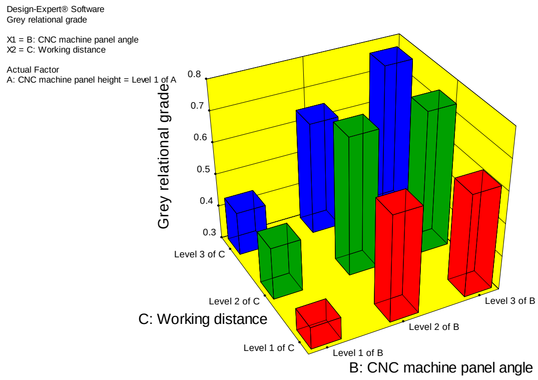

Figure 19 : General factorial effects of the interaction between the CNC machine panel angle and the working distance

The low wrist and shoulder abductions results lower human performance when combined with low elbow abduction. On the other hand, high wrist and shoulder abductions for higher age group male results better performance when combined with low elbow abduction. The Figure 19 reveals that the lowest human performance resulted at CNC machine panel angle of 30 degrees used with working distance of 10 cm while as, highest performance is resulted at panel angle of 90 degrees when combined with working distance of 30 cm. Also high multi-performance characteristic observed at 60 and 90 degrees panel angles when used with 20 cm working distance. Furthermore, higher moderate performance appeared at CNC machine panel angle and working distance combinations of 90 degrees and 10 cm, 60 degrees and 10 cm and 60 degrees and 30 cm, respectively. However, lower moderate performance emerged at CNC machine panel angle and working distance combinations of 30 degrees and 20 cm and 30 degrees and 30 cm, respectively. It can be concluded on the basis of 3D factorial effects that overall performance of younger age group males was better because of low elbow abduction at CNC machine panel angle of 90 degrees irrespective of working distances. Also, the overall performance was better due to moderate shoulder abduction at working distance of 20 cm irrespective of machine panel angles. Figure 20 shows three-dimensional (3D) view of general factorial effects of interaction between CNC machine panel height and working distance.

Low elbow and shoulder abductions results lower human performance when combined with low wrist abduction. On the other hand, moderate elbow and high shoulder abductions for higher age group male results better performance when combined with low wrist abduction. The Figure 20 reveals that the lowest

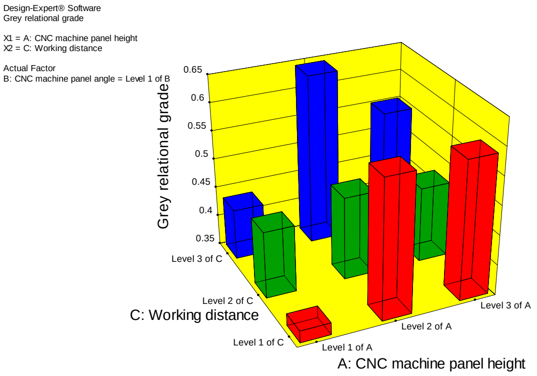

Figure 20 : General factorial effects of the interaction between the CNC machine panel height and the working distance

Human performance resulted at CNC machine panel height 90 cm used with working distance 10 cm while as, highest human performance is resulted at panel height 110 cm when combined with working distance 30 cm. Moreover, higher moderate performance exhibited at CNC machine panel height and working distance combinations of 130 cm and 10 cm, 110 cm and 10 cm and 130 cm and 30 cm, respectively. However, lower moderate performance emerged at CNC machine panel height and working distance combinations of 110 cm and 20 cm, 130 cm and 20 cm, 90 cm and 20 cm and 90 cm and 20 cm, respectively. It can be concluded on the basis of 3D factorial effects that overall performance of higher age group males was better due low wrist abduction at working distance 30 cm irrespective of CNC machine panel heights. Also, the overall performance was better due to moderate elbow abduction at110 cm panel height irrespective of working distances.

The residuals of the multi-performance characteristic (the grey relational grade) were checked to ensure that various assumptions were satisfied. To perform *model adequacy or diagnostic tests*, checks were made using *Design Expert software*. Figure 21 shows the normal probability graph of the studentized residuals.

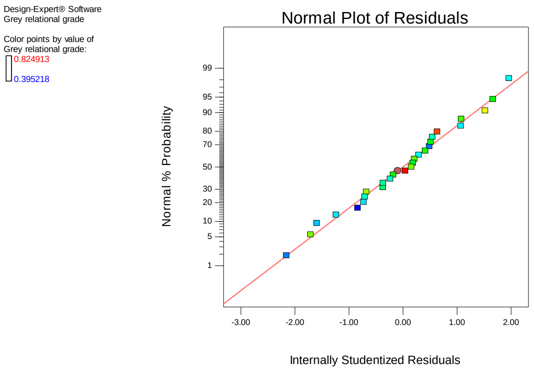

Figure 21: Normal probability plot of studentized residuals

Figure 21 shows that the normal plot of residuals fall more-or-less in line with the ideal plot. The observed pattern was also not overly abnormal, and the residuals followed a normal distribution. On observing the normal probability graph, the assumption of normality was easily concluded to be satisfactory.

Table 8 : Results of the analysis of variance

Sy-mb-ol	HCMI para-mete-rs	Deg. of freed.	Sum of squa-re	Me-an sq-uare	F-rat-io	P-value	Contri-bution (%)
A	CNC mach-ine panel height	2	0.016	7.803E-003	9.13	0.009	5.71
B	CNC mach-ine panel angle	2	0.088	0.044	51.6	□ 0.01	31.42
C	Work-ing dista-nce	2	0.020	0.010	11.7	0.004	7.14
AxB	Inter-	4	0.0	0.0	26	0.	32.50

	action between panel height and angle		91	23	.6	001	
BxC	Inter-action between panel angle and work-ing dista-nce	4	0.014	3.553E-003	4.16	0.041	5.00
AxC	Inter-action between panel height and work-ing dist.	4	0.048	0.012	14.2	0.001	17.14
Error		8	6.835E-003	8.544E-004			2.14
Total		26	0.28				101.05

3.3.2. Analysis of variance

ANOVA and the F-test were used to determine the significant HCMI parameters. The ANOVA results from *Design-Expert software* are presented in Table 8.

The purpose of ANOVA was to investigate which human-CNC machine interface parameter/s significantly affected the multi-performance characteristics. This investigation was accomplished by separating the total variability of the grey relational grades, which was determined by the sum of the square deviations from the total mean of the grey relational grade in terms of the contributions by each HCMI parameter and the error. The %age contribution of each parameter to the total sum of the squared deviations was used to evaluate the effect of changing the HCMI parameter on the performance characteristic. In addition, the F-test was used to determine which HCMI parameter had a significant effect on the performance characteristic. Usually, a change in an HCMI parameter has a significant effect on the performance characteristic when the F-value is large. Table 8 indicates that the F-value was highest for the working distance. The ANOVA results for the grey relational grade are listed in Table 8.

The ANOVA results show that all the three HCMI parameters, i.e., the CNC machine *panel height*, *panel angle and working distance* and the three interactions, i.e., between the CNC machine panel height and the panel angle, between the CNC machine panel height and the working distance and the CNC machine panel angle and the working distance significantly affected the multi-performance characteristics of the older male-CNC machine interaction environment. The results also showed that the *CNC machine panel angle* was the most significant HCMI parameter affecting the multi-performance characteristic because it had the highest %age contribution (31.42%) amongst the selected individual parameters. Table 8 shows that the %age contributions of the other parameters, in decreasing order of magnitude, were as follows: the interaction between the CNC machine panel height and the panel angle (32.5%), the interaction between the CNC machine panel height and the working distance (17.14%), the working distance (7.14%), the CNC machine panel height (5.71%), and the interaction between the CNC machine panel angle and the working distance (5.00%).

3.3.3. Confirmation test

After determining the optimal levels of the HCMI parameters, the next step was to verify the %age change of the grey relational grade between the predicted and the experimental values for the optimal combination. Table 9 compares the results of the confirmation experiment using the optimal HCMI parameters ($A_2B_2C_3$) obtained using the proposed method.

Table 9 shows that the grey relational grade improved from 0.576 to 0.626 (an improvement of

8.68%), indicating that the optimal combination of the higher age group male-CNC machine interface parameters was sufficient to meet the requirements.

Table 9 : Confirmation test results

	Optimal HCMI parameters		
	Prediction	Experiment	% improvement
Level	$A_2B_2C_3$	$A_2B_2C_3$	
Search time	620 ms	800 ms	
Motor action time	960 ms	1350 ms	
Applied force	200 mv	150 mv	
Grey relational grade	**0.576**	**0.626**	**8.68**

IV. Discussion

The World Health Organization (WHO) and the Occupational Safety and Health Administration (OSHA) consider work related musculoskeletal diseases 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.

In this study, the performance of males in the age group of 42-46 years was significantly affected upon varying the CNC machine *panel height, panel angle* and *working distance*. Human performance was measured in the present study using the dependent variables *search time, motor action time* and *applied force* on the CNC machine panel keys. The multi-performance characteristic results indicated that males in the age group of 42-46 years showed significantly different performance depending on the investigated levels of the CNC machine panel height, panel angle and working distance. The results of this study indicated that the optimum combination of HCMI parameters consisted of a CNC machine panel height of 110 cm, a panel angle of 60 degrees and a working distance of 30 cm. The study also indicated significant interaction effects between the CNC machine panel height and the panel angle, between the CNC machine panel height and the working distance and between the CNC machine panel angle and the working distance. A confirmation test showed that the optimal combination of the human-CNC machine interface parameters was sufficient to meet the requirements.

From an ergonomic perspective, it is essential that the work place design of a CNC machine environment be compatible with the biological and psychological characteristics of the human operators. The effectiveness of a human-CNC machine combination can be greatly enhanced by treating the operator and the CNC machine as a unified system. When the CNC operator is viewed as one component of an HCMI system, the human characteristics pertinent to the ergonomic design are the physical dimensions and the capabilities for data sensing, data processing, learning, etc. Quantitative information about these human characteristics must be coordinated with data about the CNC machine characteristics to maximize human-machine integration. Applying ergonomics to the design of a HCMI can not only help increase machine performance and productivity but can also enable the human operator to feel comfortable and secure. As most companies have currently acquired CNC machines to be competitive, it is strongly suggested that the ergonomic and safety aspects be thoroughly considered.

In this study, the effects of the panel height, the panel angle and the working distance on the performance of CNC machine operators were explored with respect to the search time, the motor action time and the applied force on the keys of machine panel. Male subjects were selected in the age group of 42-46 years. The variables of the CNC machine panel height, the panel angle and the working distance were found to be statistically significant. These statistically significant variables indicated the positive role of anthropometric characteristics on the performance of older male operators in an HCMI environment. Therefore, these variables must be considered in the ergonomic design of a human-CNC machine interface environment. Our findings implied that the CNC machine panel angle was the most significant factor compared to the other two factors, i.e., the CNC machine panel height and the working distance. Further, the three interactive effects i.e., between the CNC machine panel height and the panel angle, between the CNC machine panel height and the working distance and between the CNC machine panel angle and the working distance were found to be statistically significant. The analysis also revealed that the factor of the CNC machine panel angle had a significant effect at all three levels of the panel height that were explored in the present study. Furthermore, the CNC machine panel angle was found to be a significant factor for all three levels of the working distance.

V. Conclusions

This study presented an effective approach for optimizing the HCMI environment with higher age male operators using multi-performance characteristics based on a combination of the Taguchi method and grey relational analysis. The conclusions that were drawn from the results of the present study are given below.

i) The combination of the parameters and their levels for the optimum multi-performance characteristics of a HCMI environment using higher age group male operators was $A_2B_2C_3$ (i.e., a CNC machine panel height of 110 cm, a panel angle of 60 degrees and a working distance of 30 cm).
ii) The panel height significantly affected the performance of a male operator working on a CNC machine. Thus, the multi-performance characteristic showed that the CNC machine panel height was an important factor to consider in the ergonomic design of an HCMI environment.
iii) The levels of the CNC machine panel angle significantly affected operator performance in a HCMI environment. The panel angle should therefore be given due consideration in the ergonomic design of a CNC machine interface environment.
iv) The working distance appeared to be a significant factor in the HCMI environment of the present study, and it is therefore suggested that the impact of working distance should not be neglected when designing an HCMI environment.
v) The %age contributions of the CNC machine panel angle, the working distance and the panel height were 31.42, 7.14 and 5.71, respectively.
vi) An improvement of 8.68% in the multi-performance characteristics, i.e., the grey relational grade, was achieved using the approach presented here.
vii) The minimum musculoskeletal strain posture for a male group that was 42-46 years of age was found to correspond to a 130-cm CNC machine panel height for panel angles of 30, 60 and 90 degrees, with the next lowest strain posture values at the 110-cm and 90-cm panel heights, in that order.
viii) The anthropometrically comfortable posture for operators corresponded to a 60-degree CNC machine panel angle for working distances of 10, 20 cm and to a 90-degree for 30 cm working distance.
ix) A significant interaction effect between the CNC machine panel height and the panel angle (32.5% contribution) led to the conclusion that an ergonomic database exists in the form of an optimal CNC machine panel height for a particular panel angle and vice-versa.
x) The significant interaction effect between the CNC machine panel angle and the working distance (5.00% contribution) also indicated an important ergonomic database in the form of an optimal CNC machine panel angle for a particular working distance and vice-versa.
xi) A significant interaction effect between the CNC machine panel height and the working distance (17.14% contribution) led to the conclusion that an ergonomic database exists in the form of an optimal CNC machine panel height for a particular working distance and vice-versa.

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