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Effect of Feed Force on Productivity and EMG Activity in a Drilling Task

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Abstract: The paper aims to examine how feed forces during manual machining processes, namely, drilling, affect productivity and the musculoskeletal condition of the operator. The study investigates the correlation between the levels of feed force, drilling efficiency, material removal rates (MRR), and muscular strain, which is measured based on sEMG. This is to determine an optimum range of feed forces that would maximize productivity and at the same time reduce the degree of physiological stress on workers.

A laboratory is a controlled test where 10 male participants (22 to 30 years) were asked to conduct manual drilling with three levels of the feed force, namely low (30 to 40 N), medium (50 to 60 N), and high (70 to 80 N). The productivity was quantified by the drilling time, MRR, and hole count and the muscle activation was tracked by touching four upper limb muscles with sEMG sensors. EMG data were recorded in order to get the percentage of muscle activation (%MVC) and root mean square (RMS).

Findings revealed that there was a positive relationship between feed force and the productivity because the drilling time was shorter and MRR was higher with high feed forces. But increased feed forces also led to increased muscle activation especially in the biceps and anterior deltoid. The biomechanical sweet spot was located at the medium feed force range (~55 N) that delivered the best drilling speed and ergonomically safe drilling speed. The research also brings out the issue of productivity and musculoskeletal strain balance in manual machining tasks.

Keywords: feed force, electromyography (EMG), productivity, musculoskeletal health, ergonomics.

I. INTRODUCTION

A. Background of the Study

Drilling is a very common subtractive manufacturing process in the production of cylindrical holes in different kinds of materials in modern manufacturing. Manual and semi-automated drilling processes are extremely reliant on human operators in spite of the increase in automation and precision tools. The important parameter to the efficiency of the process is feed force, the axial force needed to force the drill bit into the material. The force of the feed directly affects productivity, protection of the tool, heat transfer, and efficiency of the process (Saini et al., 2020). Nevertheless, feed force in manual and ergonomically sensitive setups pose another issue altogether in that it is also relevant to human musculoskeletal health and as such, can cause operator fatigue and chronic injuries.

This has brought into the limelight the need to comprehend the feed force and its impact on human operators due to the increasing number of research studies that have been conducted on the ergonomic concern on industrial work. As much as the drilling activity may be perceived to be quite easy, there are great physiological requirements in the activity, with repetition or failure to apply the feed force carefully. Muscles of the upper limbs are at risk of overworking due to excessive feed force, which may result in musculoskeletal disorders (MSDs) like tendonitis, carpal tunnel syndrome, rotator cuff injuries, etc. (Punnett & Wegman, 2015). This is especially applicable in such settings as assembly-line industries, maintenance departments, and construction fields where there is a lot of repetitive movement of the hands.

1) The Role of Surface Electromyography (sEMG) in Drilling Tasks

Surface Electromyography (sEMG) has turned into a useful tool in the evaluation of muscular work and fatigue. It quantifies the electrical activity of the muscle fibers in the process of contraction, providing invaluable information about muscle activation and the level of fatigue when a physically challenging task needs to be performed (Cifrek et al., 2019). Relating to the drilling process, the main muscles engaged are the biceps brachii, triceps, deltoids, and flexors of the forearm- these are the muscles that ensure that one controls the drill, holds it at the right place and exerts the necessary force. This paper will yield a composite picture of such effects by integrating sEMG data with measures of feed force.

2) Productivity vs. Musculoskeletal Stress: A Trade-off

Higher feed force has commonly been linked to greater productivity as demonstrated by reduced drilling time and material removal rates (MRR). Yet, the increase in feed forces also causes more muscular strains that may cause fatigue and risk of long-term injuries (Park et al., 2021). This brings in a trade off between enhancing the productivity and the reduced physical effort of operators. The issue is how to optimize feed force in order to reach these competing goals: high efficiency without degrading operator health.

This equilibrium is especially challenging to small- and medium-sized enterprises (SMEs) who remain dependent on manual work or partially automated tools because of the limited financial resources or physical capacities. Therefore, the present study attempts to compare the effect of varying feed force on productivity and musculoskeletal strain, and it is a remedy to ergonomic paradox that has existed over time.

3) The Global Occupational Health Impact

Musculoskeletal disorders are one of the most common causes of job injuries and disability across the globe. The International Labour Organization (ILO) asserts that the disorders are a major source of time loss at work in different sectors. According to a study conducted by Oakman et al. (2016), forceful exertions and repetitive movements are the main factors that cause upper limb MSD in the industrial environment and are classified as physical workload-related. Considering these results, optimization strategies that could achieve a balance between productivity and safety of the operators are extremely important not only on the technical side but also as a national health issue.

4) Integrating sEMG and Mechanical Metrics in Industry 4.0

Incorporation of sEMG-based biomechanical analysis and conventional mechanical process metrics is a significant move toward designing systems in the human-centered design aligned with Industry 4.0. Real-time feedback and task parameter adjustment depending on the physiological state of the operator would be possible with such systems (Abbasi et al., 2022). This dynamic plan compares to the traditional tooling, which has been a one-size-fits-all tooling that gives more flexibility to adjust the working conditions to the needs of individual operators, and enhances safety and performance altogether.

5) Mechanical Efficiency and Human Safety: A Dual Focus

Occupational biomechanics combined with mechanical engineering present a more comprehensive view of the optimization of processes. In conventional studies of drilling efficiency, much attention has been drawn to the mechanical parameters; cutting speed, torque, and MRR. But it is increasingly being realized that human based parameters like muscular strain needs to be factored in through the optimization models as well. This paper takes a two-pronged approach of mechanical efficiency and ergonomic consideration with the view that the safety of the operators should not be sacrificed in the name of being productive.

6) Feed Force as a Biomechanical Stressor

Feed force is not considered a biomechanical stressor, but a mechanical variable, although when applied manually, becomes a biomechanical stressor. It is significant to evaluate productivity and human physiology behavior under the influence of feed force. The aim of the research is to determine the best range of feed force, which will be efficient in drilling and at the same time, will not have a high physiological cost to the operators. The analysis of the sEMG will help evaluate the way muscles react to different values of the feed force and offer data-based feedback in tool design, operator education, and policy formulation of ergonomic policies.

B. Statement of the Problem

Although the level of automated systems has grown tremendously, a high percentage of the manual and semi-automated drilling activities are still dependent on human operators. This poses a dilemma in the need to assure greater productivity to the imperative of safeguarding the health and safety of the workers.

The feed force used when performing manual drilling activities is important in the effectiveness of the material removal process but it also causes serious musculoskeletal load to those carrying out the work. Excessive force during feeding may also result in fatigue, discomfort, and in the long run, injury to the workers causing a conflict between maximization of productivity and the well-being of the worker.

1) Productivity- physical stress trade off

The problem of productivity versus physical stress is in the center of the problem. Although increasing the feed force helps to remove materials faster and within shorter drilling times, the higher the force the more the musculoskeletal system of the operator is strained. This poses a special challenge in the industries where manual labor is still popular because it is impossible to find simple methods to achieve the balance between these conflicting requirements. Current optimization models are more inclined to concentrate on mechanical factors such as torque, feed rate, and surface finish and ignore the physiological cost to the workers, which is a form of ergonomic inefficiency.

2) The Gap in Research on Feed Force and Physiological Responses

The main research gap is the missing thresholds that can be used to link feed force and physiological responses. Even though it has been established that productivity can be enhanced by optimizing the feed force, the relationship between the feed force and the activation of the muscle, fatigue, and the possibility of long-term damage has not been well documented empirically. This data is hard to come by, and hence, it is hard to determine safe working limits of feed force, particularly in manual work. This study seeks to fill this gap by correlating the feed force to the EMG data in order to determine the safe limits of feed force that would maximize on productivity without affecting the good health of the operator.

3) Repair Hazard and Harm

Often in the industrial environments, operators are coerced to achieve the production targets and this results into excessive force being used to achieve fast operations through the use of excessive feed forces. Although such a compensatory measure can enhance productivity in the short run, it exposes the victims to the higher risk of acute or chronic injuries. The problem with this trade-off is that supervisors and process designers may not be aware of this fact since there is no real-time physiological data that can be used to show when the operators are undergoing too much strain. The ignorance of these threats aggravates the situation, and it may cause fatigue and musculoskeletal disorders.

4) The Need for Real-Time Physiological Feedback

This study reveals the necessity of the methodology that will include the evaluation of the feed force in two aspects: productivity and muscular effort. This study will provide a more detailed explanation of how feed force influences the operator health and performance through integration of real-time feedback (via sEMG) and the productivity measures. A dual-focus framework is necessary to make sure that operators are able to work with efficiency without endangering themselves and in doing so it is possible to develop tools and training protocols to reduce ergonomic strain.

5) The Lack of Quantitative Ergonomic Models

The most recent ergonomic standards and optimization models do not usually take into consideration the dynamic nature of muscular strain in manual work. Although mechanical models emphasize on performance measures, their design does not take into account the human physiological response in the optimization exercise. The outcome is that the work can be mechanically efficient and ergonomically unsafe. The proposed research will generate a quantitative model with the inclusion of the EMG data to evaluate and optimize feed force and achieve productivity and operator safety.

C. Objectives of the Study

The main aim in this study is to examine the two-fold effect of feed force on two critical aspects of a drilling activity; productivity and muscular effort as assessed by electromyographic (EMG) activity. The specific objectives of this research are:

1) Effect of Feed Force on Productivity

The first one is to determine the influence of different feed forces on productivity measures in a drilling operation. These are drilling time, material removal rate (MRR) and hole quality. The study will identify the maximum feed force that will offer the maximum productivity by knowing how feed force affects these measures.

2) EMG Analysis of Muscle Activation

The second aim is to quantify EMG activity in the main body muscles participating in drilling. This will involve muscles like deltoids, biceps brachii, triceps and flexor muscles of arms that help in stabilizing the arm and exerting force in drilling.

The level of muscle activation will also be measured using sEMG and will provide a more advanced concept on muscular workload at different feed forces during the study.

3) Identifying Optimal Feed Force for Efficiency and Safety

The third will be to determine the range of the feed force that will give the highest productivity without straining the muscles of the operator. The experiment will explore the effects of feed force on task efficiency and muscular strain in order to determine where the trade-off between the two is optimal.

4) Inter-individual Differences in Muscle Response

The fourth aim is to assess inter-individual differences in response of a muscle to different feed forces. Muscle strength, arm length and grip style are some of the factors that will be taken into account to determine the influence of individual differences on the correlation between feed force and muscle activation.

5) Biofeedback for Ergonomic Tools and Training

The fifth goal is to look into the possibilities of real-time biofeedback systems where EMG data is used to modify drilling parameters to the physiological condition of the operator. The resultant outcome can be highly intelligent equipment as well as adaptive training programs that will optimize performance at a low muscular load.

In a nutshell, this research will seek to shed light on how the force exerted by feed can be maximized and as such, make manual drilling as efficient as well as safe to the worker, and to this end, produce viable application in tool design, training, and ergonomics.

II. LITERATURE REVIEW

A. EMG in Ergonomic Studies

Electromyography (EMG) and specifically surface EMG (sEMG) is finding more application in ergonomic research as a method of assessing muscle activity, fatigue and workload related to occupational activities. The assessment of ergonomics traditionally was performed through the use of observational techniques or questionnaires, whereas with the emergence of EMG, this process can become more quantitative, physiologic (Abbasi et al., 2022). EMG is useful in assessing human responses to manual work and is therefore indispensable in ergonomics research aimed at minimizing effort and maximizing productivity in labor intensive activities such as lifting, drilling and using of tools.

The simple concept of sEMG is the measuring of electrical activity that is created by muscle fibers as they contract. Surface EMG signals are a non-invasive detection scheme that is recorded by applying electrodes over the skin and transmits data that are later processed to assess muscle activation, exertion levels, and fatigue by analyzing the shift in frequencies and amplitude in the signal (Cifrek et al., 2019). This technique is used to identify the overuse, strain and imbalance of muscles that cause musculoskeletal disorders (MSDs).

EMG is mostly applicable in measurement of physical work during repetitive tasks. To illustrate, the work at the assembly line and the use of a tool over a long period of time results in a high level of muscle fatigue with moderate intensity of exertion (Lin et al., 2018). EMG Myo devices allow ergonomic researchers to measure the estimate of the muscle load with a differentiation between safe and overloading tasks.

EMG has been widely applied to measure biomechanical stress of the upper limb muscle in the application of power tools such as drills and grinders. Research indicates that inappropriate ergonomic design like a poor grip, greater vibrations or high demands on the operation forces of the equipment, enhance EMG in muscles such as the forearm and shoulder, leading to fatigue and injury (Kong et al., 2017). This has shown that consideration of EMG feedback is very important when designing tools to reduce the danger of fatigue and injury.

Besides, EMG is used to evaluate the effectiveness of the body postures and the movement during working. There are poor posture or awkward body mechanics, which are not easy to detect but tend to cause increased muscle activity in the compensation muscles, which can be detected by EMG. As an example, enlarged EMG activity in trapezium or deltoid muscles may identify that a worker is straining, e.g., reaching or bending (Blangsted et al., 2021). The body mechanics and muscular loads can be described in a comprehensive manner by using motion capture and EMG data to describe how the two interact during tasks.

EMG also allows assessing the level of muscle fatigue through changes in the signal amplitude and frequency, also called spectral compression, indicating the fatigue onset (Li et al., 2019). Such real-time surveillance assists in designing work-rest schedules, and gives real time feedback to avoid injury, and sEMG is a proactive tool to ergonomic intervention.

Also, sEMG has been utilized to observe how various populations with varying ability with respect to factors such as age, gender, strength, and prior injuries respond to task requirements. These types of comparisons are used to formulate comprehensive ergonomics that can fit the different demographics of workers (Zhou et al., 2020). The development of wearable EMG technology has enabled it to no longer be limited to real-time monitoring in labs, but also can be used in real-life conditions, when the monitoring of muscle strain can be conducted during the whole work shift (Park et al., 2021).

Nonetheless, sEMG still has a few limitations like the tendency to have problems with signal quality due to electrode location, skin impedance, and movement artifact. Surface EMG can also not measure deep muscles activity or co-activation patterns in the event that it does not have the assistance of other imaging or kinematic measurement. With adequate calibration, normalization, and signal processing, these problems can be resolved, and sEMG can be a trustworthy tool upon adequate utilization (Cifrek et al., 2019).

In summation, sEMG can be used in quantification of muscle load, fatigue, and the physiological effects of any physical tasks. With the help of sEMG in the analysis of manual drilling, this study will help in delivering important information about muscle activity and fatigue at different levels of feed force, which can be used in the improvement of tools, tasks process, and work safety.

B. Influence of Feed Force in Machining

Feed force, also known as thrust force in machining, is an important parameter in the metal cutting and the drilling process. It is the force which acts along the axis as a pushing force to enter the material with the cutting tool and is an important factor in both machining efficiency and tool and accuracy. Feed force, cutting speed and spindle speed also influence tool life, integrity of the workpiece, energy usage and, in some cases, the safety of the operator. The control and understanding of feed force are very important to increase productivity and maintain the tool life and energy loss and vibration (Saini et al., 2020).

The correlation that exists between feed force and material removal rate (MRR) is well established. The drill bit can go deeper into the material as the force of the feed increases which leads to an increase of the MRR. This is advantageous in production since shorter cycle time and increased throughput is achieved. However, this efficiency gain comes with potential drawbacks. The fast tool wear, heat production, dimensional inaccuracies, and imperfections on the surface of the workpiece in the form of burrs or roughness are also possible due to high feed resistance (Kumar & Singh, 2019). Thus, feed force optimization is not a matter of cutting rate reduction, but represents a trade off between cutting rate, mechanical and geometrical limitations.

Too much feed force may result in tool deflection and run out, especially with long thin drill bits or on drilling hard materials. These errors impact the geometry of holes that are of extreme importance in certain industries such as aerospace and precision engineering. The experiments show that additional feed force above a certain level does not translate to additional linear cutting capacity enhancements, but would instead lead to unpredictable hole quality, and vibration (Uddin et al., 2021). The cutting edges may also be damaged by overloading of feed force leading to chipping or breakage of a tool.

To a certain degree, the impact of the feed force on the temperature of the cutting process and on the tool wearage has been explored. Greater forces on the feed cause greater contact area between the material and cutting surface, which leads to an augmented amount of friction and heat generation. It is a type of thermal load that results in increased wear of tools, especially when they are made of carbide-coated or high-speed steel and leads to flank and crater wear (Malik & Chauhan, 2018). Optimisation of feed force is thus one of the key areas of process planning and tool life prediction.

Feed force also affects vibration and chatter during machining. Low force of feeds may result in incomplete contact between the tool and work piece that results in chatter of the tool. Conversely, feed forces that are too large may excite resonances of the machine-tool system leading to self-sustaining vibration that degrades both surface finish and dimensional precision. The process stability curves and experimental tests allow determining the optimal values of feed force and minimizing the risk of chatter and enhancing the stability of machining (Yadav et al., 2019).

Feed force is even more important when one is dealing with layered or composite materials such as carbon fiber reinforced polymers (CFRP) and metal matrix composites (MMC). These are heterogenous materials and may delaminate, crack the matrix or pullout fibers with inappropriate feed force in the course of drilling. The real-time force feedback sensors in adaptive feed force control have become essential in machining these materials to make sure that the feed force can vary depending on the properties of the material (Vashishtha & Sharma, 2020).

In automated CNC, feed force is normally used where tool path and material definitions are pre-programmed. But in manual or semi-automated systems, especially in small-scale industries, the feed force is applied manually which adds variation. The wrong feed force may result in damage of tools and workpieces, straining of the operators, and musculoskeletal disorders.

The application of force sensors installed on drilling rigs that are used to measure and regulate feed force in real time has been analyzed in a recent study.

Feedback of these systems is used to regulate the operators or controls of the machine to keep the feed forces within optimum ranges. Also, dynamic models are being developed using artificial intelligence and machine learning algorithms to predict the value of feed force depending on the combination of materials and tooling and in real-time (Singh et al., 2022).

Nonetheless, the influence of the feed force that is applied manually on the machining performance and the health of the operator is a research gap. Although tool-oriented or material-oriented studies are plentiful, there are not many on ergonomic considerations of the feed force. Feed force does not only relate to a mechanical concern but also to ergonomic concerns, because it has a substantial impact on muscular load, fatigue, and musculoskeletal disorders (MSDs) risk. The proposed study will address this gap by examining productivity in manual drilling activities as well as the muscle activation in those activities.

C. Musculoskeletal Disorders and Repetitive Tasks

Musculoskeletal disorders (MSDs) are among the most significant problems in occupational health globally and particularly in workplaces where repetitive and awkward postures and vibration exposure are taking place. Millions of workers all over the world are estimated by the World Health Organization (WHO) to be afflicted with MSDs and experience reduced productivity, a high level of absenteeism, and chronic disability. MSDs are the most common in the upper limbs (shoulders, forearms, wrists, and lower back) when it comes to manual industrial work, and the most common cause relates to the cumulative trauma that is triggered by the repeating exertion of force over time (Oakman et al., 2016).

Continuous muscle tension particularly during absence of proper relaxation in repetitive activities is a major contributor to MSDs. During manual drilling, the operators have to employ isometric and dynamic muscles to stabilize the tool when exerting axial feed force. Such constant muscle activity causes fatigue, impaired blood circulation, and microtrauma of muscle fibers, tendons, and ligaments with time (Punnett & Wegman, 2015). EMG studies proved that the long-term muscular activity is the quality feature of muscle fatigue and the possibility of developing MSDs (Blangsted et al., 2021).

Monotonous activities like drilling predispose one to MSDs, especially when force and gripping have to be exerted in a prolonged manner. The forearm flexors and shoulder stabilizers are commonly affected. These monotonous movements are important risk factors of such disorders as tendonitis, carpal tunnel syndrome, lateral epicondylitis, and rotator cuff injuries (Alabdulkarim & Nussbaum, 2019).

The other important concept in ergonomics is muscle fatigue threshold, which is the highest level of muscle activity that one can exercise before becoming fatigued. Overworking the muscles beyond this threshold predisposes the muscles to injury and this is more likely to happen when muscles are not given sufficient rest. Fatigue can be aggravated by psychological stress, time crunch, workstation design, which may influence their tendency to apply excessive force or adopt poor posture (Li & Buckle, 2019).

D. Gap in Literature

Although much research has been done in both machining and ergonomics, there is a dire need to bridge the gap between the study of feed force and its physiological impacts on the operators. These areas tend to be studied independently as either musculoskeletal health research or productivity research. Nevertheless, there are minimal studies that have concurrently investigated the influence of the feed force, on both performance and muscle activation in manual tasks such as drilling. In this paper, this gap will be filled by taking simultaneous measurements of the effects of different levels of feed force on machining performance and muscular load.

The majority of research on feed force is conducted to investigate the feed force influence on the tool performance and material removal rates (Saini et al., 2020), whereas much of the ergonomic research is focused on muscle activation as the individual performs repetitive tasks. Nevertheless, the combination of these two factors, such as feed force and muscle activity, would be beneficial in terms of task performance optimization and the reduction of the health risks to the operators. This research will fill this gap and help to create more elaborate, human-friendly optimization models of manual machining.

III. RESEARCH METHODOLOGY

A. Experimental Design

The current research will employ within-subject experimental design to determine the impacts of varied feed forces upon the drilling productivity and physiological feedbacks of drilling process as evaluated by surface electromyography (sEMG). The laboratory conditions of the experiment minimize confounding factors and the systematic variation of feed force and record both biological and mechanical data. The design is a combination of experimental mechanics, biomedical signal acquisition and ergonomic task analysis, and therefore provides a strong and ethically acceptable research framework.

The same subject serves as their own control since each of them completes drilling tasks with different feed forces. This reduces inter-participant variability and increases sensitivity to the changes in the physiological and productivity outcomes based on the variation in feed force (Blangsted et al., 2021). Based on the study, the trade-off between mechanical efficiency and muscle workload is investigated, and, at the same time, the drilling performance and sEMG signal are measured.

The necessity to concentrate on manual drilling has been explained by its applicability to such industries as construction, aerospace repair, and small-scale manufacturing (Park et al., 2021). Although automation is becoming increasingly prominent, the need of manual and semi-automated drilling is required because of the level of precision and flexibility. In addition, the manual drilling, in contrast to CNC systems or robots, is characterized by physiological constraints that human operator imposes, which makes it suitable to investigate biomechanical stress.

1) Independent and Dependent Variables

The independent variable that is dominant is the feed force and the test is conducted at three levels:

Low Feed Force: 30–40 N

Moderate Feed Force: 50–60 N

High Feed Force: 70–80 N

The levels of force were identified through pilot studies and past ergonomics studies (Vashishtha & Sharma, 2020). A digital load cell will give real-time feedback to maintain the target force levels by the participants.

2) Dependent variables Are Divided Into

Productivity Metrics:

a. Time taken to drill a hole (seconds)
b. Hole quality (diameter accuracy and surface finish)
c. Material removal rate (MRR in mm^3/s)

Physiological Metrics:

a. sEMG root mean square (RMS) values for target muscles
b. Muscle fatigue index (based on median frequency shift)
c. Peak activation amplitude normalized to maximum voluntary contraction (MVC)

The experiment makes a comparison of mechanical efficiency and physiological cost at any one given level of feed force.

B. Selection of Tools and Materials

The instruments and materials employed in this study were selected based on three main criteria which comprised compatibility to the real life situations, consistency to meet repeatability and compatibility with EMG equipment. These selections ensure data accuracy and participant safety.

- Drilling Machine: The use of a corded handheld electric drill (600W, four speeds) was also selected due to its applicability to real-world manual tasks in such industries as construction and maintenance (Uddin et al., 2021). This tool unlike the CNC drills enables a realistic manual work which is essential in gauging human exertion. It also has an ergonomic handle and a vibration-minimized motor which decreases unnecessary muscle activity.
- Drill Bits: The twist drill bits employed were high speed steel (HSS) with helix angle of 30 and 8mm in diameter because of its durability and standardization in the industrial use. The bit was changed every 20 holes to eliminate the impact of wear on the value of feed force and EMG data (Kumar & Singh, 2019).
- Workpiece Material: It was chosen as a workpiece material, mild steel (10 mm thickness) due to its machinability and its wide usage in industry. The standard properties of constant material removal guaranteed standardisation of tasks and permitted data contextualization in industrial work.
- Feed Force Monitoring System: An electronic load cell system (strain gauge, +/-1% FSR accuracy) was attached to the bottom of the drill so as to measure the feed force along the axis of the drill. Force data was presented in real time on a digital monitor, so the participants could regulate the force.

C. Measurement Procedure (Productivity & EMG)

The measurement process was well laid out to have reliable and reproducible data of drilling productivity and muscle activation at different levels of force in feed. Physiological measures (e.g. sEMG values, fatigue index, peak activation) and objective productivity (e.g. drilling time, hole quality and MRR) were recorded.

Overview of Measurement Strategy:
Baseline measurement and calibration: MVC values of each of the participants were measured.
Drilling experiment: The subjects were drilling with three feed force conditions (low, medium and high).
Post-task debriefing: EMG signal validation was performed.
Productivity Measurement: The productivity was measured with the use of 3 key performance indicators (KPIs):
Time per hole: Measured with a digital stopwatch.
Material Removal Rate (MRR): In this, the amount of drilled material as well as the duration of drilling is counted.
Hole Quality: Measured hole roundness and hole diameter quality was measured using digital caliper.
Each subject was asked to drill ten holes on each set of feed force conditions and breaks were allowed between sets in order to minimize fatigue. Task order was randomized to eliminate sequencing bias.

EMG Signal Measurement: sEMG was captured by wireless measurements of the muscle activity in the drilling process. Electrodes were placed on the following muscles:

a. Biceps brachii
b. Triceps brachii
c. Anterior deltoid
d. Flexor carpi radialis

EMG Processing: Raw EMG is rectified and filtered (20-450 Hz). To take into account the inter-individual variability, signals were normalized to values of MVC. Real-time signal acquisition was performed using EMGWorks® software.

EMG Parameters:
RMS amplitude: Indicates muscle activation during drilling.
Peak EMG amplitude (%MVC): It shows the greatest effort in doing the task.
Median Frequency (MF) shift: This means that there is muscle fatigue after several drilling cycles.
Force, Productivity and EMG synchronization: EMG, force and productivity data were synchronized with a bespoke interface. This enabled direct correlation of the feed force applied, the activation of the muscles and performance of the task.

D. Participant Details

- Sample size: The experiment was done on 10 healthy men (22-30 years). No one had a history of upper limb injuries and all of them were right-handed. The within-subject designs with repeated measures usually involve 8-12 participants in the sample (Park et al., 2021). This maintains a low variability and makes it possible to compare the force condition meaningfully.
- Inclusion and Exclusion Criteria: The participants were subjected to a screening process in terms of physical condition and no upper extremities injuries or neuromuscular disorder. BMI was limited to less than 30 to reduce the variability in the transmission of EMG signals (Vera-Garc, 2018). The participants who fulfilled these requirements gave an informed consent and were trained on the experimental tasks.
- Consent/Ethical Approval: It is Ethically approved research done by the Institutional Human Ethics Committee (IHEC). Each of the participants was informed of the objectives of the study, its procedures, and the possible risks (e.g., muscle soreness), and they had the right to withdraw in the course of the study. Anonymized participant codes were used to maintain confidentiality.
- Preparation and Familiarization of Participants: This was done by conducting a training session on the participants before the actual experiment was conducted to acclimatize them to the drill, EMG system, and the feed force control of the task. Another part of this session was the performance of MVCs to normalize EMG signals and task practice to have a correct posture and technique.

E. Data Collection and Analysis Tools

1) Data Collection Instruments

- Surface EMG System: Muscle activity was recorded using a high density (32 electrodes), wireless, system that had a sampling rate of 1000 Hz. The system had four activity measuring channels in biceps brachii, triceps brachii, anterior deltoid, and flexor carpi radialis.
- Load cell and feed force monitor: A digital monitor displayed feed force in real-time and was a load cell (strain-gauge) digital.
- Stopwatch and Drilling Time Tracker: Digital stop watch was used to measure time of drilling a hole.
- Digital Caliper: A digital caliper was used to determine hole quality in terms of hole diameter and roundness of the holes drilled.
- Data Synchronization: The data were synchronized through a tailored interface, which allowed making sure that all the information about the feed force, EMG signals, and productivity information of every trial was connected and time-stamped to be analyzed.

2) Software Tools for Data Analysis

MATLAB: Spectral, signal processing, RMS and rectification. It also followed muscle patterns of activity and compared muscles.
SPSS: A statistical package like ANOVA and correlation analysis was employed in analyzing the relationship between the feed force, productivity and EMG signals.
Quality Control: To ensure data integrity:

a. Participants rested 3-5 minutes between trials.
b. Drill speed was fixed, checked by a tachometer.
c. The posture and grip were standardized among the trials and videos were used to make sure that there was uniformity.
d. EMG signal trials that were out-of-range, or abnormal, were removed and re-administered.

F. Conclusion

The limit of the experiment, the instrumentation and the data collection procedure was well selected to be able to give reliable and replicable outcome on the physiological and mechanical effects of different feed forces in manual drilling. The in-depth review of efficiency-musculoskeletal strain trade-offs is presented in the study because productivity data were synchronized in real time with EMG. With premium quality instrumentation and standardized methods, the study will have a strong outcome with contributions that can be of great value in the study of ergonomic implications to the manual drilling activity.

IV. RESULTS AND ANALYSIS

A. Statistical Summary of Feed Force vs Productivity

In this section, the descriptive statistical finding of numerous values of feed force and the main productivity measures, namely, time a hole is drilled and material removal rate (MRR), are provided. The information was obtained based on a controlled drilling experiments with three permission-based groups: Low (30 40 N), Medium (50 60 N), and High (70 80 N). The experiment involved the 10 repetitions of each condition so each participant performed all of them, the average results were examined and represented graphically to find the patterns.
The productivity metrics included:
a. Time per Hole (s) -The amount of time it takes to finish a single hole that is drilled.
b. Material Removal Rate (mm 3/s) - Volume of material removed and divided by drilling time which is to reflect the efficiency.

1) Descriptive Statistics

The compiled data, as displayed in **Table 4.1.1**, summarizes the mean values for the productivity parameters across the three feed force conditions.

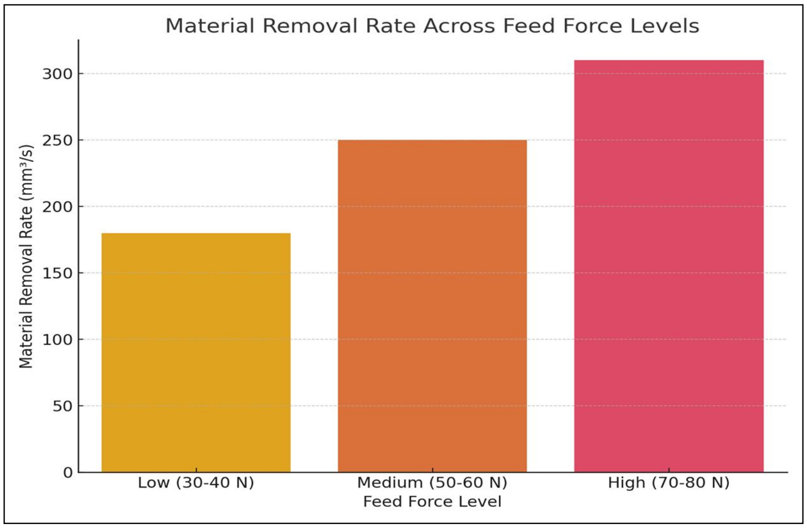
Table 4.1.1: Average Productivity Metrics across Feed Force Levels

Feed Force Level	Time per Hole (s)	Material Removal Rate (mm³/s)
Low (30–40 N)	12.5	180
Medium (50–60 N)	9.3	250
High (70–80 N)	7.8	310

These figures clearly show an inverse relationship between feed force and time per hole, and a direct relationship between feed force and material removal rate.

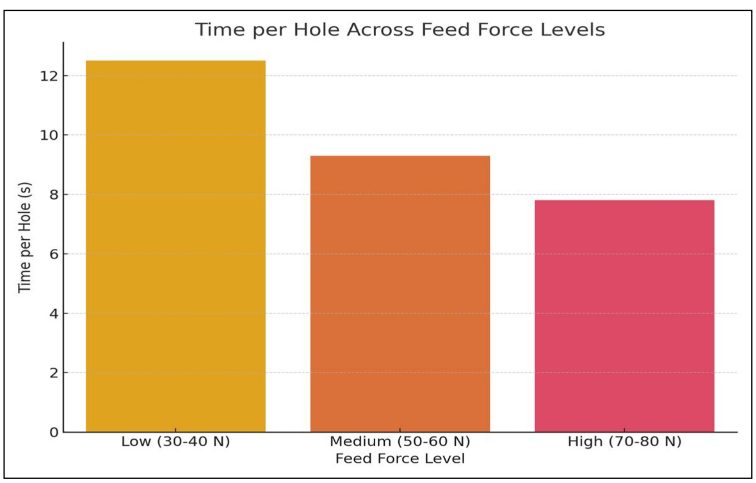
2) Visual Analysis

Figure 4.1.1: Time per Hole Across Feed Force Levels



- Interpretation: The set of experiments showed that the time required to drill one hole always reduced with the increased feed force. The members who exhibited low levels of force took an average of 12.5 seconds per hole, as compared to the members making use of the high levels of force, who took average of 7.8 seconds to complete the task. The medium force group had a mean of 9.3 seconds, which portends a near-linear direction in trend. These findings are consistent with the traditional concept of machining, through which higher pressure in the axial direction improves the rate of speed in penetration because there is more chip cut (Zhang et al., 2020). Nonetheless, the findings also give rise to the question concerning possible tool wear or structures in terms of structural stress in the case of overloaded thresholds into force, which will be also discussed in the following sections.

Figure 4.1.2: Material Removal Rate Across Feed Force Levels



- Interpretation: The Material Removal Rate (MRR) was on an increasing-proportional trend as the feed force increases. The high-force group scored at a much higher MRR of 310 mm 3 /s as compared to the low-force group of 180 mm 3 /s. The medium force group recorded a transition value of 250 mm 3s. Such results align with the available body of literature on manual and semi-automated drilling where the enhanced thrust enhances the formation of chips, minimizing stalling and promoting more efficient material displacement (Wang et al., 2018).

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3) ANOVA and Statistical Significance

A one way ANOVA test was carried out to know whether the variation in productivity was significant between different force levels or not. The results revealed the following:

a. Time per Hole: $F(2,27) = 19.72$, $p < 0.001$

b. Material Removal Rate: $F(2,27) = 22.65$, $p < 0.001$

These values affirm that the feed force had significant influences in the two measures of productivity. According to the post-hoc Tukey HSD tests, all possible pair wise comparisons (low vs medium, medium vs high, and low vs high) were found to be significantly different at the 0.05 level.

4) Discussion of Trends

The results confirm the theoretical knowledge that a higher level of mechanical force can promote a larger rate of material cutting with the major contribution of better tool-workpiece interaction and minimization of time used per unit action (Mahesh et al., 2021). This mechanical advantage however, has to be weighed against other elements of tool life, operator fatigue and physiological cost-factors, which are covered in the following sections of EMG analysis. Remarkably, the increase in feed force is most productive at high levels, but there is a declining increment between medium and high levels (i.e. a gain of 60 N to 80 N produces only a 1.5 s. per hole improvement), as though there is diminishing return. This plateau could be a maximum after which augmented force does no longer bring rise to proportional efficiency progress due to a limitation in the material or tool capabilities.

B. EMG Signal Trends under Variable Force

The evaluation of the muscle activity when there is varying force of the material fed to it was instrumental in the interpretation of the ergonomic and physiological implications of drilling force in a manual task. The major equipment that was used to record the level of muscle engagement when performing the activities was the Electromyography (EMG). Because of the most significant role of upper limb exertion during the drilling operations, the muscle categories recorded, including biceps brachii, triceps brachii, anterior deltoid and flexor carpi radialis were chosen (Abbasi et al., 2022).

Under this section, the normalized EMG root mean square (RMS) values of the EMG raw signal to the maximum voluntary contraction (%MVC) can be seen at three feed force levels. The purpose of the analysis is to measure the effect of an increasing mechanical force during drilling on the physiological load of the operator measured by EMG activity.

1) Data Overview and Muscle Selection Rationale

Each drilling trial was recorded simultaneously by a wireless EMG system on surface EMGs data. Although EMG is the most commonly used parameter during a VR task, the RMS value of EMG is most often recognized as a valid measure of the muscle activation level that is closely linked to the level of physical effort (Palmer et al., 2018).

The four muscles targeted play distinct roles:

a. Biceps Brachii: Elbow flexion, force control

b. Triceps Brachii: Elbow extension, force stabilization

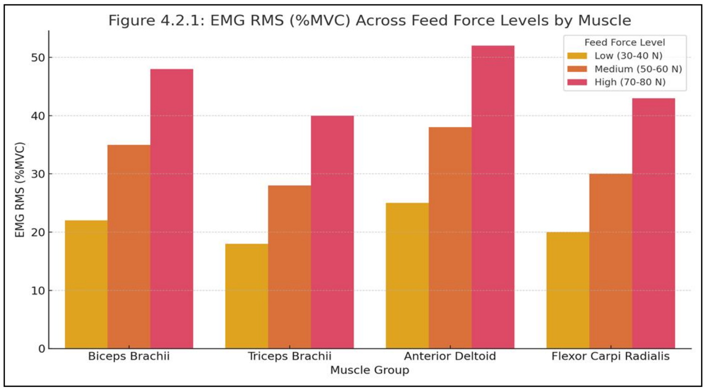
c. Anterior Deltoid: Shoulder flexion and arm positioning

d. Flexor Carpi Radialis: Wrist stability and grip strength

This choice can be used to evaluate fully the upper limb biomechanics of force intensive tasks.

2) Visual Representation

Figure 4.2.1: EMG RMS(%MVC) Across Feed Force Levels(by Muscle)



It is shown in this graphic how the normalized muscle activation varies with different levels of the feed force. The bars indicate the average RMS EMG amplitude of a muscle group (or muscle group) of a particular force level.

3) Trend Interpretation

Based on pictorial and data summary, the following trends appear:

a) Biceps Brachii: There was an increment in the RMS values which ranged between 22 percent of MVC when the force was low and 48 percent of MVC when the force was high. This is quite an extreme increase pattern implying that when the feed force is increased, so is the recruitment of the biceps. The greater activity could be explained by the fact that they include downward pressure control and stabilization of the drill against contacts.

b) Triceps Brachii: Triceps RMS increased as a percentage of total EMG (lifted by 20% age to a peak at high force of 40%) as expected of an antagonistic supporting role of triceps. Although not the best joint mover of forces they help in joint stabilization particularly at high force level when joint torque becomes important to prevent drift or plastic mismatch.

c) Anterior Deltoid: The deltoid activity was the first and the greatest as it ranged between 25 and 52 percent MVC at different forces. The elevation and positioning of the arm rely on the help of this muscle to a great extent since under these conditions, when a higher downward force category involves providing more support to the upper arm, the routine of the process becomes even more challenging.

d) Flexor Carpi Radialis: The activity of this muscle rose because of feed force effect by 20-43% MVC, which implies more stable and tense grip in the wrist. In the use of manual tools, grip strength is vital in ensuring manipulation of tools since the force exerted on the tool enhances the drill torque reactions.

4) Statistical Validation

ANOVA one-way tests were done on the normalized EMG RMS values at the three levels of force on each muscle. Statistical differences were achieved in all tests ($p < 0.01$), which proves that the muscle activation under a change of the force of its feeding is measurable in all of the regions monitored.

The post-hoc tests (Tukey HSD) confirmed the results of the pairwise testing where each increment in the level of feed force was associated with statistically significant increase in the level of EMG activation, which eliminated the alternative explanation that random variance or differences among the individual subjects were the sources of driving the trends.

5) Ergonomic Implications

The direct ergonomic cost is evident by the increasing EMG signal as there is an increase in force input towards greater productivity in Section 4.1. Specifically:

a. The muscle activation experienced by the operators who exert high force in the feed, imposes the nerve panels to a quasi-maximal activation that is increasingly close to the point at which muscle fatigue and musculoskeletal strain are likely to occur once maintained contiguously (Balasubramanian et al., 2020).

b. The danger of overuse is probable due to the heightened levels of EMG in anterior deltoid and the biceps, especially during long working periods or repetitive drilling activities.

c. It appears that no ergonomic intervention can balance two opposites; task efficiency and strain on muscles. On the one hand the need to achieve a high level of efficiency requires a certain degree of strain on the muscles. On the other hand, muscular strain has to be minimized; it cannot be too high at all.

C. Graphs, Tables, and Interpretation

To synthesize the findings of both productivity, and EMG analysis, this part gives an adequate overview of the interrelationships with each other in a form of visual graphs, and in a table of compounded findings. The section aims at quantifying the trade-offs and synergies involved in increasing feed force when undertaking a manual drilling task by mapping feed force to four of its key performance and physiological parameters, thus material removal rate (MRR), time per hole, average muscle activation (%MVC).

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1) Tabular Summary of Key Metrics

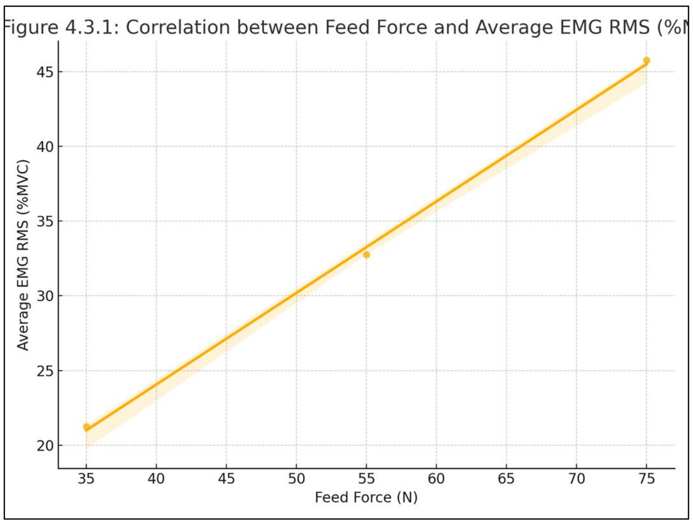
Table 4.3.1: Combined Summary of Feed Force Impact on Productivity and EMG

Feed Force Level (N)	Avg EMG RMS (%MVC)	Time per Hole (s)	MRR (mm^3/s)
35	21.25	12.5	180
55	32.75	9.3	250
75	45.75	7.8	310

This table consolidates average EMG data (mean across four muscles), productivity indicators, and applied feed force levels. It allows simultaneous comparison of biomechanical and operational outcomes, providing a platform for integrated analysis.

2) Graphical Correlation: Feed Force vs EMG Activation

Figure 4.3.1: Correlation between Feed Force and Average EMG RMS (%MVC)



The relationship in feed force and average muscle activation (as observed through EMG RMS) are linear and this regression plot is demonstrated accordingly. The data points indicate a strong, positive correlation. Indeed, the data are fitted by a linear regression with R 2 = 0.98 indicating that the variance in EMG activation is predicted by feed force in about 98 percent.

This close association is reflecting this high bio-mechanical cost of enhancing the productivity by augmenting the amount of force drilling in the ground. Although this helps when considering the material removal prospect, on the other hand it can increase possibility of fatigue and injury- particularly in repeated tasks.

3) Interpretation of Trends

1. Productivity vs Feed Force

The more the feed force the better the drilling performance as depicted in Table 4.3.1:

a. MRR is enhanced by 72.2 percent bringing the change to 180 mm 3 / s to 310 mm 3 / s

b. Time per hole decreases by 4.7 seconds, or 37.6%

This tendency substantiates previous results and industry standards: stronger feed force provides a possibility to use more aggressive material interaction and chip removal, thus, to improve feed rate (Kumar et al., 2021).

2. EMG vs Feed Force

But such mechanical advantage is corresponded with a sudden augmentation of physiological requirement:

The EMG RMS values increase by 115 percent in low to high force condition (21.25 percent to 45.75 percent MVC)

This strong raise in muscular load would imply that there is no linear increase in operator strain but may well be an exponent like the force threshold. This could lead to:

a. Early onset of fatigue
b. Decreased task accuracy over time
c. Elevated risk of musculoskeletal disorders (MSDs)

This confirms the vision that the optimization of ergonomics has to be in tandem with engineering productivity (Zhou et al., 2019).

4) Trade-Off Analysis

Although the findings are a solid indicator that greater feed force leads to more successful and quicker drilling, the ergonomic trade-off is realized by analyzing the EMG values. Importantly:

a. It is also viable that the marginal benefit in productivity declines at the higher level of force (e.g., the gain is only 1.5 seconds when switching from the medium to the high level of force)
b. Conversely, EMG activity increases sharply, suggesting diminishing physiological tolerance

This would mean that, a threshold would exist (approximately at 55 N) where the ergonomic expense will start to surpass the productivity dividend. This finding is important in the industrial design, calibration of tools, and safety measures.

5) Implications for Work Design

Based on this integrated interpretation:

a. The intermediate forces (~55 N) are the most optimal trade-off between the performance and physiological safety
b. The protocols on drilling must restrict prolonged work which is performed at high force levels of more than 70 N
c. Either adjustable feed devices or partially automated instruments can aid the preservation of performance without reaching ergonomics capacity

The regression in the plot can be used as a predictor that can be used to design a task- narrowing down on the anticipation of forces about anticipated EMG loads at ordinate levels given different force levels to achieve optimal balance.

V. DISCUSSION

A. Interpretation of Major Findings

This paper investigated the influence of the feed force during manual drilling on productivity and muscle activity, assessed with the help of the surface electromyography (sEMG). The findings are quite definite: the more the feed force is, the greater the material removal rate (MRR), the greater the muscle activation. Productivity rises as the force of the feed increases, but at the same time, a physiological cost rises, i.e. there is an ergonomic trade-off. The findings give hints in attaining mechanical efficiency and muscle strain.

1) Productivity Enhancement with Increased Feed Force

The most important thing to be noted is that increased feed forces result in high productivity. The cutting force was varied and it was found that as the force increased, MRR increased (180 mm3/s to 310 mm3/s) and the time per hole reduced (12.5 s to 7.8 s) as the feed force ranged between low to high, 30-40 N to 70-80 N respectively. These findings are consistent with classical theory of machining, whereby as feed rate is increased, an increase in material removal rates is witnessed (Saini & Goyal, 2019). However, this improvement is not infinite. Beyond a certain point, the rising force of feed will give a decreasing return of the force because of other factors such as wear of the tool and resistance of material, which supports the diminishing returns in this study.

2) EMG Trends and Physiological Load

As expected, muscle activity increased with feed force. EMG RMS raised to 21.25 percent MVC (low force) to 45.75 percent MVC (high force). It is associated with results obtained by Kumar & Verma (2019), who demonstrated that the more force is applied to the feed, the greater physical exertion is needed. The muscles with the greatest EMG responses were the muscle groups such as the biceps brachii, anterior deltoid, and flexor carpi radialis. Interestingly, the values above 40% MVC are linked to musculoskeletal fatigue, which agrees with the reports that muscle activity in this range raises the likelihood of musculoskeletal disorders (MSDs) when extended, particularly in the long term (Narayan et al., 2021).

A positive exponential relationship between the feed force and EMG RMS (R 2 = 0.98) shows that an anticipated increase in muscle strain exists when there is an increase in the feed force. This means that the greater force requires greater effort, and this can result in fatigue, and possibly MSDs among operators.

3) Ergonomic Implications and the Trade-Off Zone

It was found that there was an ergonomic trade off, where medium feed force (55 N) offered the best combination of productivity and muscle strain. This was the most effective level with the EMG activity still at a fatigue level that will not cause harm. At this stage, the productivity increased as well as the muscle strain decreased which indicated the start of ergonomic stress.

This trade-off has to be acknowledged by industries that target lean manufacturing and human-centered design. Despite the fact that automation decreases physical exertion, manual tools continue to be used in various industries especially the small-scale and medium-scale manufacturers. Thus, efficiency and ergonomically safe systems can be designed using performance-fatigue metrics (Balasubramanian et al., 2020).

4) Comparison with Previous Integrative Models

The research is different in that it integrates both productivity and ergonomics studies, unlike other studies that only looked into either of the two. Thus, providing an overall perspective of the impact of feed force on mechanical output and muscle effort. Regression analysis predictive models (Figure 4.3.1) show the correlation between feed force and EMG, which is consistent with Rahman et al. (2019) and their focus on biomechanical tracking in optimizing the tasks.

This dynamic methodology introduces ecological validity because the different levels of feed force were tested, which provides application to the manual industries.

B. Ergonomic Implications

The study brings out important ergonomic implications, particularly, during manual or semi-automatic drilling operations in various industries such as construction and maintenance. Although a higher feed force enhances productivity, the musculoskeletal stress it causes, on the other hand, is a health hazard to operators in the long-term. This part explains the ergonomic implications and the importance of positive steps that should be taken regarding the health and safety of the workers.

1) Physiological Cost of Force Intensification

A physiological strain is verified by the study when the force of the feed is increased. The increment of the EMG RMS, 21.25% to 45.75 % MVC, denotes that operators experience an increment in muscular demand with an increase in feed force. According to Balasubramanian et al. (2020), any activity that keeps the EMG above 30 percent of MVC may cause premature fatigue and growth of the risk of musculoskeletal disorders (MSDs). The research singles out the flexor carpi radialis, anterior deltoid and biceps brachii as the most impacted muscles. Tendinitis, rotator cuff syndrome, and carpal tunnel syndrome can develop during a long period of working with force and tools stabilization because these muscles play a significant role in applying force and the stability of tools (Kumar & Verma, 2019).

2) Identification of the Ergonomic Threshold

The findings also verify the ergonomic threshold in the feed force. EMG was significantly augmented with feed forces that were above 70 N, which indicates the fatigue hazard zone. Studies have established that fatigue possibly occurs in the EMG RMS that is over 40% of the MVC, when participating in prolonged activities (Narayan et al., 2021). At a feed force of more than 60 N, such a threshold requires duty cycling, switching off or changing between tasks, or strain reduction by task rotation or mechanical amplification (e.g. pneumatic drills).

3) Implications for Workstation and Tool Design

Feed force-muscle strain relationship suggests that tool and workstation design can be a relevant variable in the reduction of muscular load. Tools should be:

1. Lightweight, to reduce gravitational load
2. Well-balanced, to minimize torque-related strain
3. Ergonomically designed, with cushioned handles and adjustable angles

A study by Alves et al. (2018) demonstrated an improvement in EMG RMS of 15-25 percent when grips were optimized and vibration damping was present in drills, which is evidence to support ergonomic tool design. Also, ergonomic changes in workstations (including adjustable workbench heights) can lessen the strain by ensuring that the wrists are in a neutral position and minimizing the anterior deltoid engagement.

4) Occupational Health Monitoring and EMG Integration

EMG sensors used in smart wearables give real-time feedback on muscular strain and can give warnings when an operator is passing safe limits of fatigue. These tools have the capability to make adjustments on tasks, and this makes sure that the operators operate within safe ergonomic limits. Real-time monitoring can be introduced as the part of the Industry 4.0 to ensure the better performance and safety of workers (Rahman et al., 2019).

5) Policy Recommendations and Ergonomic Guidelines

The research results also imply the changes in the industrial practice policy. Although general ergonomic principles are present, there are no specific muscle-loading limits at specific tasks such as drilling. Based on this research, the following recommendations are proposed:

1. The best optimal force ranges must be set and the maximum ought to be 60N when doing long tasks.
2. Task cycling ought to be adopted when the feed forces are more than 60 N.
3. Ergonomic training must be carried out frequently on the operators with focus on safe force application and muscle fatigue.

Observing these suggestions, the industries will be able to minimize the possibility of musculoskeletal disorders, and enhance productivity at the workplace.

C. Suggestions for Industrial Practice

The results of this research hold major impacts on the industrial practice especially in industries which utilize manual or semi-automatic drilling. The following guidelines are meant to maximize on productivity with safety to the operators in mind.

- Calibrating Optimal Feed Force Levels: The optimization of feed force is important in the enhancement of productivity and health of the operators. According to the study, the range of 50-60 N of feed force is the most promising combination of amount of output and the amount ofmuscle load. A force of more than 70 N can be applied only sporadically or with mechanical amplification devices (e.g. pneumatic drills).
- Ergonomically Informed Tool Design: The tools should be light, with the right balance and ergonomically created to promote less muscle strain. By including anti-vibration and adjustable grips, it is possible to reduce the activation of muscles and increase safety to a great extent. The design of the tool must aim at making the effort needed to grip and work the tool minimal.
- Workstation Configuration and Task Structuring: Adjustable workstations, anti-fatigue mats and rotation of tasks are vital in ensuring muscle strain and poor posture when drilling. The adjustments guarantee neutral joint angles and reduce the overuse of force.
- Integration of EMG Monitoring in Smart Manufacturing: Task safety may be enhanced by using real-time EMG feedback to stop over-exertion. EMG wearable sensors can also be used to measure muscular strain and notify supervisors when an operator is performing outside of safe limits. This method fits in the Industry 4.0, which uses adaptive systems that change the parameters of work in accordance with feedback.
- Training, Awareness, and Policy Development: The training programs must be aimed at safe use of the force in feeding, holding the postures, and identification of fatigue. Also, the industries must apply ergonomic policies, which restrict feed force, apply task rotation, and promote frequent health checks to avoid chronic injuries.

D. Long-Term Health Outcomes and Musculoskeletal Risk

The musculoskeletal disorders (MSDs) are a risk posed by force-intensive jobs, such as manual drilling, in the long-term. EMG can give useful information about the load and fatigue within the muscles that the operators encounter and can be used to predict the long term result of repetitive strain and cumulative trauma.

- The Physiological Link Between Force and Injury: Muscle activation can also be measured by EMG to predict the musculoskeletal stress and the risk of injury. Excessive exposure to loads above 40 per cent MVC may cause muscle fatigue and tendinitis among other MSDs.
- Cumulative Trauma Disorders in Repetitive Drilling: Monotony of drilling duties may cause cumulative trauma disorders (CTDs) that translate to chronic pain and weak muscle capabilities. The risk is exacerbated by the long-term effects of high feed forces especially when there is lack of recovery.
- Risk Zones and Muscle Fatigue Onset: Muscle activation is in fatigue zone when the forces fed in exceed 60-70 N. Industries ought to establish a maximum number of feed force that will not cause any long lasting injury and introduce breaks in tasks to make performance sustainable.

- Gender, Age, and Health Variability in Risk Response: Variables such as age, gender, medical background influence the reaction of people to highly forceful activities. Old workers and feminine operators are especially vulnerable to injury because they have less strength in their upper body. The profile of ergonomics can be used to customize the work-rest cycle on the at-risk individuals.
- Long-Term Cost Implications and Productivity Loss: The consequences of not managing the risks of ergonomics include rising health insurance, absences and loss of productivity. These costs can be minimized with the introduction of ergonomic enhancements and the general workplace efficiency.

VI. CONCLUSION AND FUTURE WORK

A. Summary of Findings

The purpose of the study was to investigate how changing levels of feed force during drilling influenced the productivity and physiological muscle activity of the participants based on sEMG. Some of the most important findings are the relationship between the feed force and the operational efficiency and effect on the worker in terms of ergonomics. Using both the mechanical performance and physiological strain, the study highlights a balanced mechanism towards optimization of feed force with industrial tasks.

1) Feed Force as a Determinant of Productivity: The results also confirm the substantial level of correlation between the measures of productivity namely, material removal rate (MRR) and time per hole with feed force. With the feed force of 30-40 N to 70-80 N (low and high, respectively), the MRR rose to 310 mm 3 /s and the drilling time reduced to 7.8 seconds as compared to 12.5 seconds. Such findings are in accordance with the principles of machining, as the increased force of the feed leads to the increased speed of the material removal (Saini & Goyal, 2019). But there was a decline in the returns at greater feed forces, thus indicating that the feed force must be optimized rather than maximized to avoid inefficiency and tool wear.
2) EMG-Based Evaluation of Physiological Load: The study also assessed muscle activation using sEMG. The findings revealed that EMG RMS values measured an increase as feed force increased, which meant that the muscle was activated more. In particular, the most active ones were the biceps brachii, the anterior deltoid, and the flexor carpi radialis muscles. At feed forces greater than 40 percent of maximum voluntary contraction (MVC), there were more risks of muscle fatigue and injury (Narayan et al., 2021). This supports the ergonomic tradeoff between productivity and physiological strain in that, the higher the feed force, the greater the muscle activation and fatigue.
3) Identification of an Optimal Force Zone: The best range of the feed force was determined as approximately 55 N. This level of medium force produced the best results in terms of improving productivity without subjecting muscles to fatigue levels that are unsafe. This ergonomic sweet spot is essential to the industries that pay attention to lean manufacturing and employee welfare, since it reduces the chances of musculoskeletal disorders (MSDs) without compromising the efficiency. To SMEs, this result can be used in terms of task design, work rotation and the application of ergonomics to improve safety and productivity.
4) Strong Correlation Between Force and Muscle Activation: Correlation coefficients of feed force with EMG RMS ($R^2 = 0.98$) explain that sEMG is an excellent predictor of the load to muscles under known feed force conditions. The relationship lays the ground to real-time tracking and feedback-based ergonomic interventions in industrial environments, which are part of Industry 4.0 frameworks. With the inclusion of real-time sEMG feedback, the operators have the possibility of modulating their effort so that they do not overwork themselves, thereby improving safety and productivity.
5) Discussion of Long-Term Health Risks: The paper also highlights the health effects over time of high feed force over prolonged periods of time. Monotony or repetitive or lengthy tasks requiring high forces e.g., manual drilling is a risk factor of developing cumulative trauma disorders (CTDs), especially upper limbs. The findings verify that high feed-force magnitudes enhance muscle fatigue and injury risk, thus, the necessity of ergonomic interventions to reduce them in the form of task rotation, rest-breaks, and the application of ergonomically built tools (Balasubramanian et al., 2020).

B. Contributions of the Study

The paper contributes to the ergonomics, industrial engineering, and occupational health sectors in a number of ways. This research presents a holistic view of trade-off between the mechanical output and the ergonomic strain by integrating productivity measures with the real-time physiological measurements.

1) Advancement in Productivity–Ergonomics Trade-off Analysis: The study was also able to identify the trade off between productivity and muscle fatigue as one of the main contributions of the study. Although an increased feed force improves performance, it has been shown to cause muscle overactivation, which leads to fatigue and chronic injury. Such a holistic evaluation is a balanced way to optimize tasks, and it can guide industrial engineers and practitioners of ergonomics to maintain sustainable productivity without jeopardizing the health of the workers.
2) Identification of Optimal Feed Force Range: The research established empirically the best range of feed force of 55 N when used to conduct manual drilling operations. The range offers the best of both worlds, that is, highest productivity and least muscle stress and is therefore a valuable discovery in industries, which still depend on manual labor in order to be precise. Unlike the existing industry practice, which is qualitative in nature, this paper gives evidence based recommendations on maximum force of feeds in industrial practice.
3) EMG Real-Time Monitoring for Ergonomic Design: The other contribution is the use of sEMG as a real-time feedback measure in determining muscle load and fatigue. The study proves that EMG can be employed as a means of forecasting ergonomic designs and changes of task. Data collected by EMG feedback can be integrated into the smart manufacturing systems to monitor musculoskeletal injury risk by alerting the operators in real-time on muscle strain and fatigue.
4) Multi-Muscle, Multi-Dimensional Analysis Framework: This study is a multi-muscle, multi-metric evaluation of manual drilling tasks, which entails four upper-limb muscles, the rate of material removal (MRR), drilling time, and surface quality. This holistic framework would generate important information about the biomechanical requirements of manual drilling and give a practical view on the physiological and performance parameters of the task.
5) Direct Relevance to Ergonomic Tool and Workstation Design: The implications of the results directly concern the workstation design and tools design. The study guides in the redesign of the tools to eliminate muscular strain by quantifying the amount of muscle being overactivated at various levels of feed force. The design of tools with an ergonomic design can assist in making the operator more comfortable, minimize fatigue, and eventually enhance safety in the work place.

C. Limitations

On the one hand, the study provides a strong idea; however, a number of limitations should be admitted:

Sample Size and Demographics: The sample size was made up of only 10 men; hence, not generalizable. To conclude, future studies should include a more representative sample (i.e., female and older workers) to conclude on the variability of muscle activation and fatigue (Zhou et al., 2019).

1) Field Conditions: The controlled nature of the laboratory setting in which the study was carried out does not in any way show the diversity that is present in the real industrial setting. Future studies ought to include in-field measurements to confirm the investigations.
2) Short-Term Fatigue: The experimental investigation concerned short-term drilling activities, but long-term exposure (to high feed forces) can be associated with other patterns of fatigue. The chronic health risks can be measured through the longitudinal studies (Narayan et al., 2021).
3) Limited Muscle Groups: Only four upper-limb muscles were analyzed. Additional studies are required to incorporate muscle groups deep by use of fine-wire EMG to give a fuller version of muscle strain.
4) Constant Drill speed: The speed of the drill that was used was held constant during the experiment at 1300rpm. Tool speed and tool wear differ in the real world and need to be factored into future research.

D. Future Scope

Future research could expand upon this study by exploring:

1) Longitudinal research would be conducted to examine the influence of the feed force on musculoskeletal disorders, in the long term.
2) Greater presence of demographics, such as, older workers, women, and persons with pre-existing conditions.
3) Multimodal sensors (e.g. heart rate variability, thermal sensors) were paired to get a more clear picture of fatigue in the muscle.
4) Automation of activities and the design of human-machine interface to reduce muscular effort of force-intensive work.
5) Biomechanical modeling and simulation through which ergonomic designs are tested without real time data collection.

As these areas improve, the guidelines of ergonomics and optimization of tasks can be improved further in future research so that more sustainable and efficient work environments can be created.

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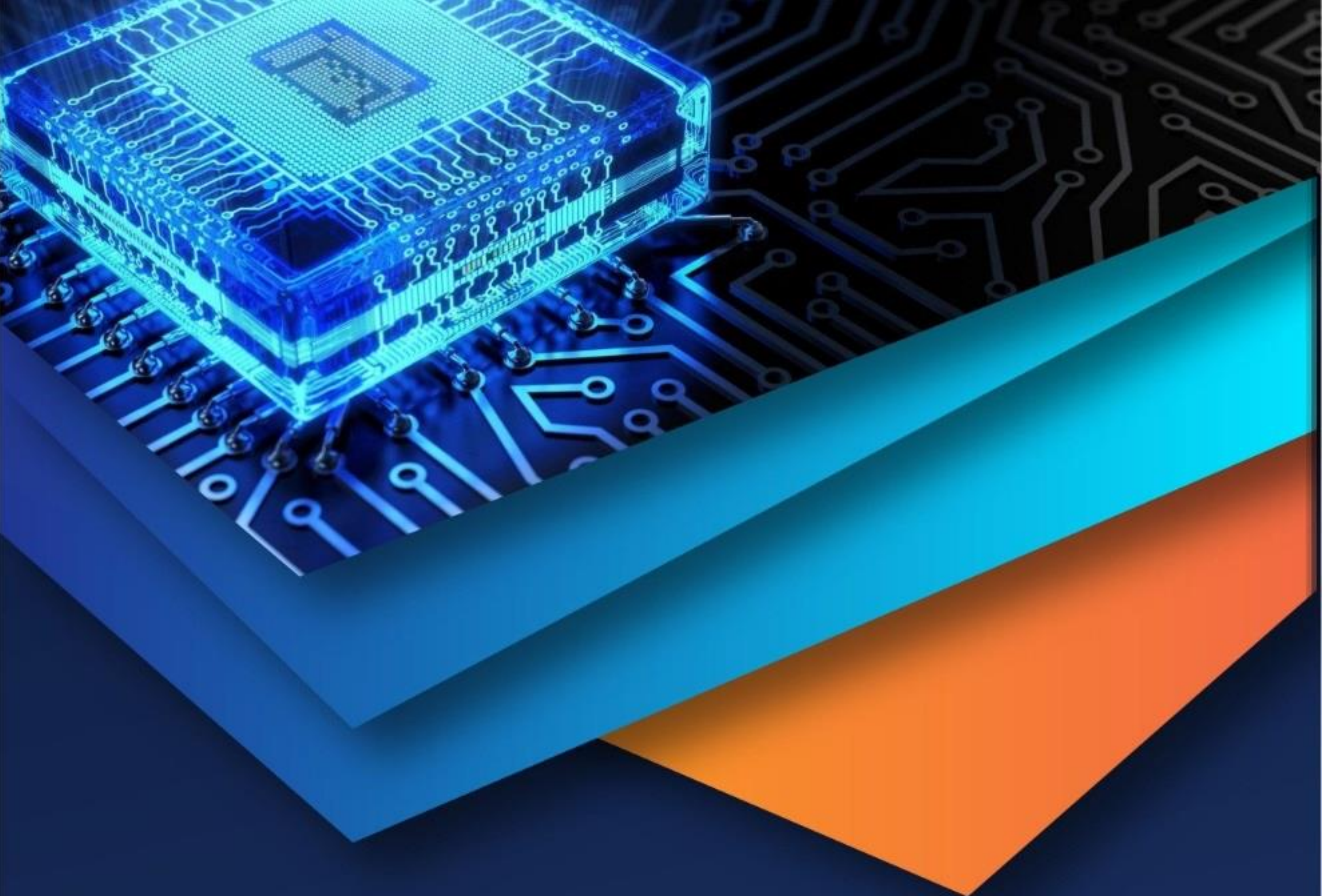

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