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Design and Development of an Ergonomic Milling Machine Control Knob using TRIZ Principles

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Abstract: TRIZ, a Russian abbreviation known as the Theory of Inventive Problem Solving, refers to a methodology for problem-solving rooted in logic and data rather than intuition. It promotes the ability to solve problems creatively. Using TRIZ tools for problem-solving such as the cause-effect-chain analysis and engineering contradiction, a new ergonomic milling machine control knob was developed for improved musculoskeletal comfort. The major improvisations from the original milling machine knob included its spherical shape design, the indentations to accommodate a lateral pinch and the addition of a rubbery material for increased sensation. In the validation test, it was found that this new and improved ergonomic milling machine control knob was able to reduce the amount of pinch force by about 72% for males and 55% for females compared to the original knob, hence potentially eliminating risks of overexertion in pinch grips. This solution potentially reduces occupational injuries and cumulative trauma disorders. An implicit benefit is that the quality of machined parts using the milling machine can be potentially enhanced due to better control of the machine knobs that could eventually lead to the reduction of rejects and reworks, which also translates to improved productivity.

Keywords: Engineering Design, TRIZ, Ergonomics, Machining, Pinch Force, Occupational Injuries, Productivity, Manufacturing, Cumulative Trauma Disorders, Musculoskeletal Comfort

Introduction

Since basic designs such as knobs require a certain amount of force and effort to be operated, knobs should be designed to accommodate people who are weak in physical strength (Shaheen and Niemeier, 2001; Thompson, 1995). Knob designs that incorporate hand-related ergonomics considerations are necessary to improve the satisfaction and maintenance of physical health at the workplace (Helander, 1995; Pinto *et al*., 1996; 2000).

The ergonomics of knob designs appear to play a role in the prevention of accidents musculoskeletal disorders, which can eventually affect the efficiency of work. Since there appear to be limited studies on ergonomic knob designs, researchers should study and work towards the design, development and assessment of an ergonomic knob that potentially reduces risks of hand-related injuries and musculoskeletal disorders.

In manufacturing and machining industries, milling machines are common equipment which are often used to machine metal, wood and other solid materials. During the milling process, the control of the milling tool's speed is vital in order to produce a good surface finish for the product. The speed is controlled by the milling machine speed control knob. Figure 1 shows an example of milling machine control knobs.

However, in most cases, it is found that the milling machine control knob can be difficult to turn. The excessive amount of force used to turn the control knob repetitively could lead to the development of hand-related musculoskeletal disorders in a long run. Hence, the problem statement can be formulated as.

Problem Statement: It is Difficult to Turn the Milling Machine Control Knob

Hence, the aim of this study is to generate a solution for this problem using some of the inventive design principles of TRIZ. The solution will potentially reduce the occupational injuries and musculoskeletal disorders of the users and increase their productivity.

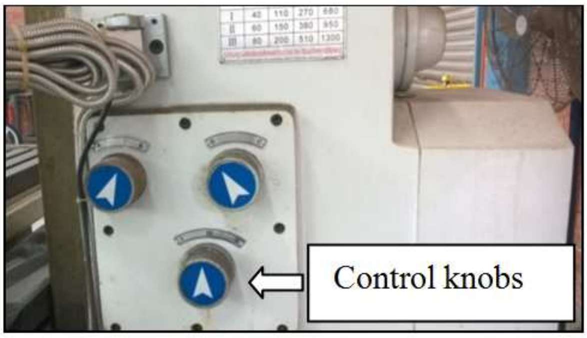


Fig. 1. Milling machine control knobs

Furthermore, the quality of the machined part can also be potentially improved as rejects and reworks would be reduced due to improved control of the machine knobs.

Literature Review

The manipulation of basic designs such as knobs using inappropriate handling techniques and excessive repetition may lead to hand injuries (Browne and O'Sullivan, 2012). Equipment with confusing control positions can increase the risks of injuries as well (Burgess-Limerick *et al*., 2010). In association with the aforesaid problems, it has been postulated that a high-quality knob design should demand minimum active finger flexion force to reduce fatigue, injury and risks of musculoskeletal disorders (Young *et al*., 2010).

Since knob manipulation requires a certain amount of force and effort, knobs should be designed to accommodate people who are weak in physical strength (Shaheen and Niemeier, 2001; Thompson, 1995). Some researchers believe that in order to minimize joint pain in elderly workers who operate knobs, it is important to adjust their seated working position so that it is less strenuous for the hands and arms (Murray-Leslie, 1991; Shaheen and Niemeier, 2001). Moreover, knob designs that incorporate hand-related ergonomics considerations are necessary to improve the satisfaction and maintenance of physical health at the workplace (Helander, 1995; Pinto *et al*., 1996; 2000).

In summary, the ergonomics and appropriateness of knob designs appear to play a role in the occurrence of musculoskeletal disorders, which can eventually affect the efficiency of work. Since there appear to be limited studies on ergonomic knob designs, researchers should study and work towards the design and development of an ergonomic knob that potentially reduces risks of hand-related injuries and musculoskeletal disorders. One of the risks of these injuries and disorders include high pinch force exertions.

Methodology

The approach chosen to solve the problem at hand and innovate the solution to the problem is known as TRIZ. This approach was selected because of its effectiveness in problem-solving compared to common creativity tools which are normally limited to brainstorming and methods which depend on intuition and the knowledge of project team members (Barry *et al*., 2015; Yeoh *et al*., 2015). These common approaches are classically described to be psychologically based with unpredictable and unrepeatable results. The following sections include explanations on the TRIZ approach, process flow, cause-and-effect chain analyses, engineering contradiction, inventive principles and proposed solution.

The Theory of Inventive Problem Solving (TRIZ)

TRIZ, a theory invented by G. S. Altshuller and his colleagues between 1946 and 1985, is a problem-solving method based on logic and data (not intuition) which accelerates the project team's ability to solve these problems creatively (Yeoh *et al*., 2015). It provides repeatability, predictability and reliability due to its structure and algorithmic approach. It is an international science of creativity that relies on the study of the patterns of problems and solutions and not on the spontaneous and intuitive creativity of individuals or groups (Barry *et al*., 2015).

TRIZ Process Flow

There are 2 tools used in the finding of a solution, which include the cause-and-effect chain analysis and engineering contradiction. Through the sets of tools involved, solutions generated are both simple and elegant to use. Figure 2 shows the overview of TRIZ processes involved in the solving the problem.

Cause-And-Effect Chain Analyses

A cause-and-effect chain analysis was done in order to identify the root cause of the problem defined in the previous section. The 5-why analysis is used in order to identify the root cause. Figure 3 shows the 5-why analysis conducted for the problem statement which states that it is difficult to turn the milling machine control knob.

Based on the 5-why analysis, it is noted that the knob is difficult to be turned mainly because it requires high force exertion by the user. In view of the knob's design alone, the reason for this high force exertion was because of the insecure grip that the users had when turning the knob. This insecure grip was caused by slippages of the fingers, which can be due to a lack of contact area to be gripped by the user. It is hypothesized that this lack of contact area is due to the knob's unsuitable shape, namely a cylindrical shape.

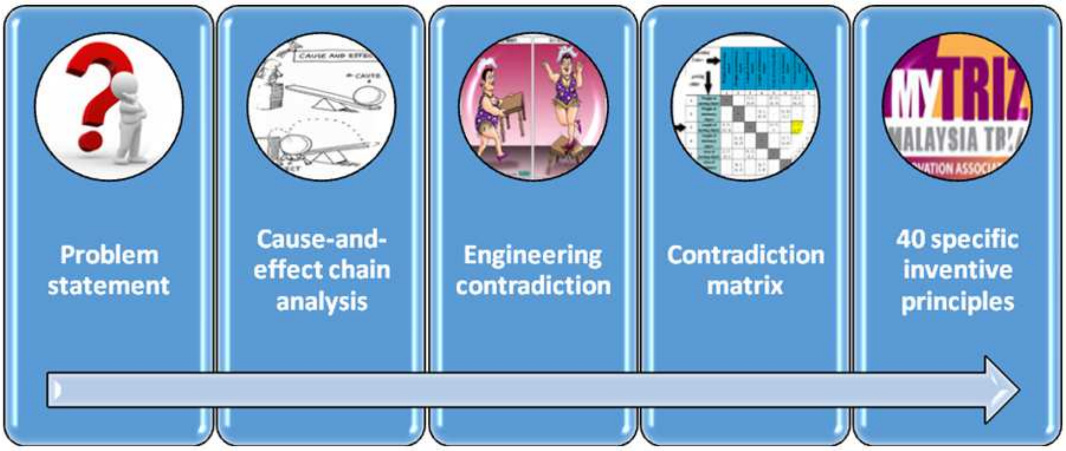


Fig. 2. TRIZ process flow

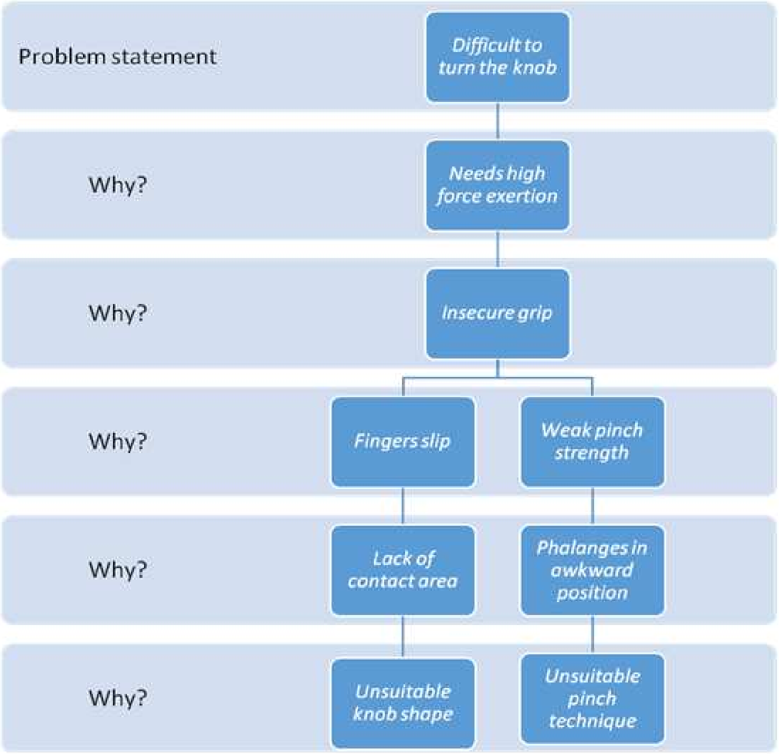


Fig. 3. The 5-why analysis for root cause identification

The slippages of the fingers could also be due to a lack of friction between the user's fingers and knob surface. This is hypothesized to be due to the choice of material (aluminium) which causes the knob's surface to be smooth and slippery. However, changing the material of the product would not be cost effective for the project. Hence, this possibility is excluded as a root cause of the issue.

The insecure grip may also be caused by a weak pinch strength, which is due to the awkward positions of the phalanges when gripping the knob. The awkward positions are hypothesized to be due to the unsuitable pinch techniques used. There are four types of pinch techniques which are commonly used, namely three point pinch, lateral pinch, pulp pinch and tip pinch (Klaiput and Kitisomprayoonkul, 2008; Mital and Kumar, 1998; Rolian *et al*., 2011; Towles *et al*., 2008).

According to Imrhan and Rahman (1995), the lateral pinch is stronger than the pulp pinch, tip pinch and three point pinch when the pinch width is 20 to 56 mm. If a guideline was set for the knob to be turned using only the lateral pinch technique to avoid excessive use of force, this potential cause of the problem can be minimized. Hence, this possibility is also excluded as a root cause of the issue.

The knob's unsuitable shape (cylindrical) can be a factor that causes high force exertion since the contact area on the cylindrical control knob is small. Based on the 5-why analysis, the root cause of the problem is identified as the unsuitable shape design of the knob (cylindrical shape).

Engineering Contradiction

The root cause was identified as the unsuitable shape design of the knob, which is cylindrical in shape. A 50 mm cylindrical knob shape would not have a large enough contact area for the phalanges of the finger to be placed on while pinching and turning the knob. With a reduction of the contact area, it is normal for users to voluntarily increase their finger force in order to compensate for the lack of normal force over the smaller area (Pressure = Normal force/Area). As a result, the pressure generated by the users tends to be larger in order for them to avoid slippages during the knob operations.

However, doing this for an extended period of time will cause the fatigue and pain in the users' hand and forearm muscles. This eventually leads to the user draining unnecessary energy from the manual work. With the identification of the root cause, the responding variables are identified to form the engineering contradiction.

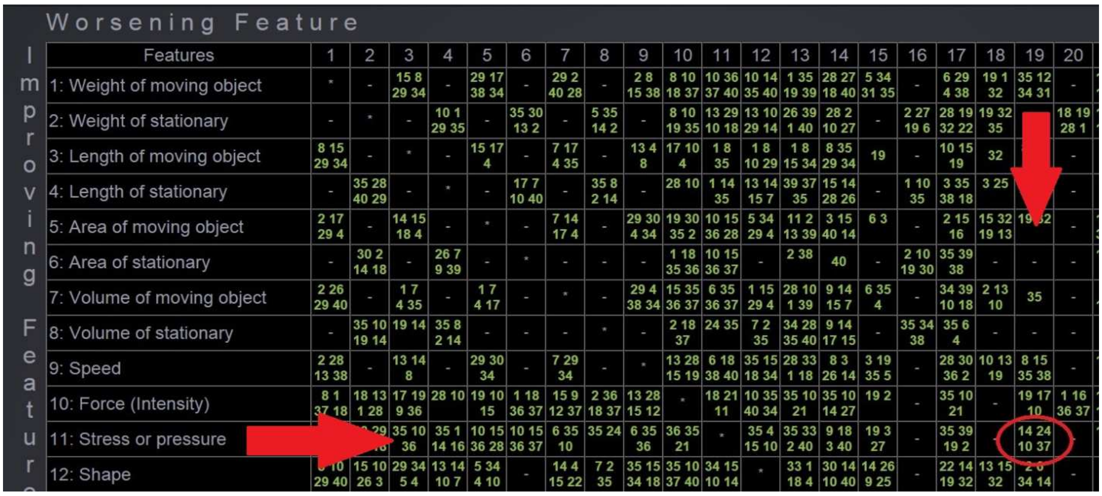
If the Knob Shape is Cylindrical, then the Stress or Pressure on the Knob Increases, but the Energy used to Turn the Knob Reduces

The responding variables identified in the statements of the contradiction's second and third line point out to two specific parameters out of the 39 system parameters identified in the TRIZ manual (Yeoh *et al*., 2015). These parameters (both improving and worsening parameters) are identified in Table 1.

Results

Since a clear engineering contradiction statement has been formed based on the problem at hand, referencing and utilizing the inventive principles in TRIZ would be a faster and more efficient method of obtaining a solution to the problem. The 40 TRIZ inventive principles are a list of known solutions developed by Altshuller through the screening of patents in order to find out what kind of contradictions were resolved or dissolved by the invention and the way this had been achieved (Yeoh, 2014; Yeoh *et al*., 2015). Studying these existing solutions inspired many TRIZ practitioners to solve new problems and imagine innovative solutions. Table 2 shows the 40 TRIZ inventive principles referenced in this study along with each principle's corresponding brief description.

In order to identify which combination of the inventive principles are to be used, the matrix of contradiction is to be referenced (Yeoh *et al*., 2015). The matrix of contradiction allows researchers to reference 2 identified system parameters extracted from the engineering contradiction statement (improving and worsening parameter) via cross tabulation in order to screen out which of the 40 inventive principles are to be used to solve the problem. Figure 4 shows a screenshot of the TRIZ contradiction matrix, where the improving and worsening features/characteristics identified allows users to narrow down the scope of inventive principle combinations to be applied as a solution to their problem.



Worsening Feature

Improving Featur

Features	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1: Weight of moving object	*	-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40	1 35 19 39	28 27 18 40	5 34 31 35	-	6 29 4 38	19 1 32	35 12 34 31	-
2: Weight of stationary	-	*	-	10 1 29 35	-	35 30 13 2	-	5 35 14 2	-	8 10 19 35	13 29 10 18	13 10 29 14	26 39 1 40	28 2 10 27	-	2 27 19 6	28 19 32 22	19 32 35	[illegible]	18 19 28 1
3: Length of moving object	8 15 29 34	-	*	-	15 17 4	-	7 17 4 35	-	13 4 8	17 10 4	1 8 35	1 8 10 29	1 8 15 34	8 35 29 34	19	-	10 15 19	32	[illegible]	-
4: Length of stationary	-	35 28 40 29	-	*	-	17 7 10 40	-	35 8 2 14	-	28 10	1 14 35	13 14 15 7	39 37 35	15 14 28 26	-	1 10 35	3 35 38 18	3 25	[illegible]	-
5: Area of moving object	2 17 29 4	-	14 15 18 4	-	*	-	7 14 17 4	-	29 30 4 34	19 30 35 2	10 15 36 28	5 34 29 4	11 2 13 39	3 15 40 14	6 3	-	2 15 16	15 32 19 13	19 [illegible]	-
6: Area of stationary	-	30 2 14 18	-	26 7 9 39	-	*	-	-	-	1 18 35 36	10 15 36 37	-	2 38	40	-	2 10 19 30	35 39 38	-	-	-
7: Volume of moving object	2 26 29 40	-	1 7 4 35	-	1 7 4 17	-	*	-	29 4 38 34	15 35 36 37	6 35 36 37	1 15 29 4	28 10 1 39	9 14 15 7	6 35 4	-	34 39 10 18	2 13 10	35	-
8: Volume of stationary	-	35 10 19 14	19 14	35 8 2 14	-	-	-	*	-	2 18 37	24 35	7 2 35	34 28 35 40	9 14 17 15	-	35 34 38	35 6 4	-	-	-
9: Speed	2 28 13 38	-	13 14 8	-	29 30 34	-	7 29 34	-	*	13 28 15 19	6 18 38 40	35 15 18 34	28 33 1 18	8 3 26 14	3 19 35 5	-	28 30 36 2	10 13 19	8 15 35 38	-
10: Force (Intensity)	8 1 37 18	18 13 1 28	17 19 9 36	28 10	19 10 15	1 18 36 37	15 9 12 37	2 36 18 37	13 28 15 12	*	18 21 11	10 35 40 34	35 10 21	35 10 14 27	19 2	-	35 10 21	-	19 17 10	1 16 36 37
11: Stress or pressure	[illegible]	[illegible]	35 10 36	35 1 14 16	10 15 36 28	10 15 36 37	6 35 10	35 24	6 35 36	36 35 21	*	35 4 15 10	35 33 2 40	9 18 3 40	19 3 27	-	35 39 19 2	-	14 24 10 37	-
12: Shape	[illegible] 10 29 40	15 10 26 3	29 34 5 4	13 14 10 7	5 34 4 10	-	14 4 15 22	7 2 35	35 15 34 18	35 10 37 40	34 15 10 14	*	33 1 18 4	30 14 10 40	14 26 9 25	-	22 14 19 32	13 15 32	[illegible] 34 14	-

Fig. 4. Screenshot of the TRIZ contradiction matrix (Yeoh, 2014; Yeoh *et al*., 2015)

Based on the system parameters identified in Table 1, it is noted that the worsening feature includes the use of energy by the moving object (parameter number 19 which is viewed horizontally across the contradiction matrix), while the improving feature includes the stress or pressure generated (parameter number 11 which is viewed vertically downward the contradiction matrix). The intersection of these two parameter references leads to a combination of inventive principles as indicated in Fig. 4.

When cross-referencing the system parameter numbers within the contradiction matrix, 4 inventive principles (out of 40 potential principles) were identified as the guideline to approach the solution to the problem:

- 24: Intermediary
- 14: Curvature
- 10: Preliminary action
- 37: Thermal expansion

Table 1. System parameters

Parameter no.	Parameter	Characteristic
11	Stress/Pressure	Improving
19	Use of energy by moving object	Worsening

Table 2. The 40 TRIZ inventive principles (Yeoh *et al*., 2015)

Inventive principles	Brief description
Segmentation	Divide object to independent parts
Taking out	Separate interfering part from object
Local Quality	Change object's structure from uniform to non-uniform
Asymmetry	Change shape of object from symmetrical to asymmetrical
Merging	Assemble similar parts to perform parallel operations
Universality	Make object perform multiple functions
Nested doll	Place one object inside another
Anti-weight	Compensate for weight of object
Preliminary anti-action	Create beforehand stresses in object that oppose known undesirable working stresses later on
Preliminary action	Perform, before it is needed, the required change of object
Beforehand cushioning	Prepare emergency means beforehand to compensate for low reliability of object
Equipotentiality	Limit position changes in potential field
The other way around	Invert action(s) used to solve problem
Curvature / Spheroidality	Instead of using rectilinear parts, use curvilinear ones.
Dynamics	Divide object to parts capable of movement relative to each other.
Partial or excessive actions	If 100 % of object is hard to achieve with given method, use 'slightly less' or 'slightly more' of the same method
Another dimension	Move object in two- or three-dimensional space
Mechanical vibration	Cause object to oscillate or vibrate
Periodic action	Instead of continuous action, use periodic / pulsating action
Continuity of useful action	Carry on work continuously
Skipping	Conduct process or stages at high speed
Blessing in disguise	Use harmful factors to achieve positive effects
Feedback	Introduce feedback to improve a process or action
Intermediary	Use intermediary carrier article or process
Self-service	Make object serve itself by auxiliary helpful functions
Copying	Replace object or process with optical copies
Cheap short-living	Replace inexpensive object with multiple inexpensive objects comprising certain qualities
Mechanics substitution	Replace mechanical means with sensory means
Pneumatics and hydraulics	Use gas and liquid parts of object instead of solid parts
Flexible shells and thin films	Use flexible shells and thin films instead of three-dimensional structures
Porous materials	Make object porous or add porous elements
Color changes	Change color of object or its external environment
Homogeneity	Make objects interacting with given object of same material
Discarding and recovering	Discard portions of object that have fulfilled their functions
Parameter changes	Change object's physical state
Phase transitions	Use phenomena occurring during phase transitions
Thermal expansion	Use thermal expansion (or contraction) of materials
Strong oxidants	Replace common air with oxygen-enriched air
Inert atmosphere	Replace normal environment with inert one
Composite material films	Change from uniform to composite materials

Table 3. Proposed actions and reasoning to use 3 selected inventive principles for solution

No.	Principle	Proposed actions	Reasoning
24	Intermediary	Rubbery material is added to increase tactile sensation.	Increased frictional force greatly helps users hold on to objects and exert force efficiently (Seo *et al*., 2008).
14	Curvature	The shape of the knob is changed to a spherical shape to increase contact area.	Spherical objects have better handling properties than cylindrical objects since they often reflect the natural handling properties of a human hand (Yuan and Kuo, 2006). This also explains why people are naturally familiar in handling sports-ball type shapes.
10	Preliminary action	Grooves are added to accommodate the finger positions in a lateral pinch grip to avoid slippages.	In order to prevent the loss of energy and effort in turning the knob, grooves can act as support to the thumb and index finger while turning the knob and the user is allowed to exert lesser pinch forces on the knob.

Proposed Solution

According to the 4 inventive principles identified, brainstorming sessions were held by the team and it was finally decided that 3 of the identified inventive principles would be utilized to develop a potentially viable solution. Table 3 shows the selected inventive principles along with the proposed actions and reasoning with regard to solving the problem.

Discussion

Based on the proposed actions drawn from the inventive principles, a new ergonomic knob is designed and developed (Fig. 5 for the design and Fig. 6 for the actual product).

The major changes from the original milling machine knob include:

- The spherical shape design
- The 2 indentations to accommodate lateral pinch
- The addition of rubbery sensation

New Ergonomic Knob Versus Existing Knob

A replica of an existing milling machine control knob is fabricated for comparison purposes in the validation test. The diameter of the control knob replica is 50 mm and the surface of the knob is filled with straight knurls, which is similar to the actual control knob on the milling machine in a company workshop. The existing control knob is shown in Fig. 7.

A total of 12 manual operators (6 males, 6 females) participated in this validation. Each participant spent a total of 2 h operating both knobs. The pinch force was recorded using the Finger TPS system and finger cot sensors, with both the knobs being mounted on a fixed structure for a constant condition (Fig. 8). The improvement of the new ergonomic knob over the existing control knob is substantial, as the ergonomic knob requires a much lower pinch force to be operated compared to the existing control knob.

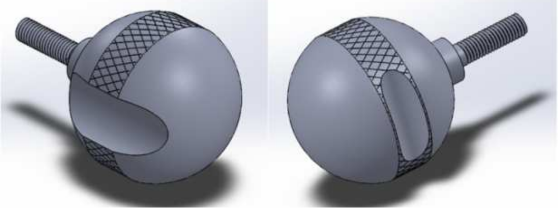


Fig. 5. Design of the new ergonomic knob

Fig. 6. Actual product

Fig. 7. Existing milling machine control knob

Table 4 shows the percentage of change between the performance of the new ergonomic knob and the existing control knob. The percentage of change is computed with the equation as shown in Equation 1. The improvement is 72.42% in average for the male participants and 55.41% in average for the female participants:

$$\begin{aligned}&Percent\ Change(\%)\\&=\frac{Second\ Knob - Milling\ Machine\ Knob}{Milling\ Machine\ Knob}\times 100\%\end{aligned} \quad (1)$$


(a) (b)

Fig. 8. Recording of pinch forces with the finger TPS system (a) Existing knob (b) New knob

Table 4. Percentage of change between performance of new ergonomic knob and the existing control knob

		Male			Female		
Participant no.	Torque direction	New knob (Force, N)	Existing knob (Force, N)	Percentage (%)	New knob (Force, N)	Existing knob (Force, N)	Percentage (%)
1	CW	1.640	14.550	88.73	1.410	7.240	80.52
	CCW	1.670	15.940	89.52	2.230	7.520	70.35
2	CW	0.800	2.270	64.76	1.490	2.790	46.59
	CCW	1.133	2.730	58.50	2.370	3.090	23.30
3	CW	0.913	4.310	78.82	2.860	4.610	37.96
	CCW	1.257	5.320	76.37	3.590	9.720	63.07
4	CW	1.000	3.570	71.99	1.170	4.410	73.47
	CCW	1.200	11.770	89.80	1.810	8.270	78.11
5	CW	1.173	1.870	37.27	3.160	6.530	51.61
	CCW	2.137	5.960	64.14	3.740	5.230	28.49
6	CW	1.173	4.710	75.10	1.270	3.270	61.16
	CCW	2.067	7.970	74.07	2.170	4.370	50.34
Average				72.42	Average		55.41

*Note: CW means clockwise, CCW means counter clockwise

Conclusion

The study's aim was to reduce or solve the difficulty in turning the milling machine control knob using some of the inventive design principles of TRIZ, such as the cause-and-effect chain analyses and engineering contradiction. As a result, a new ergonomic milling machine control knob was designed, developed and successfully tested for viability against the original milling machine control knob. It was also found that this new ergonomic milling machine control knob was able to reduce the amount of pinch force by about 72% for males and 55% for females compared to the original knob, hence potentially eliminating risks of overexertion in pinch grips.

The impact of this product transcends aspects such as safety, health and productivity. In terms of safety and health, this new knob minimizes muscle injuries during manual handling and reduces risks of musculoskeletal disorders in a long run. This eventually results in lesser visits to doctors and medical leave applications due to minor/major hand-related injuries. Worker productivity can also be improved. Manual equipment operations will be potentially more effective due to the lesser physical effort required for knob controlling activities. Instead of giving too much focus on the amount of strength needed to be exerted on the knob, workers can focus their efforts on other related tasks simultaneously. The operation tasks would also be less tiring.

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Author's Contributions

Poh Kiat Ng: Planned the research and design of the experiment. He also initiated and implemented the idea of using TRIZ tools to solve the problem. The data analyses and manuscript writing were also done by him. He was also the project leader of this study.

Kian Siong Jee: Helped in the experimental setup, pilot tests and actual experimentation of this project. He contributed to the writing of this manuscript and helped in preparing some of the literature review content. He was also the co-project leader of this study.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all the other authors have read and approved the manuscript. Hence, no ethical issues are involved.

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