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Research paper

Risk Mitigation Strategies for Controlled Descent Device Used for Emergency Rescue

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Abstract

Controlled descent devices are critical safety mechanisms designed for emergency rescue, enabling the safe descent of individuals from significant heights during emergencies. This study presents an analysis of risk mitigation strategies for a controlled descent device working on centrifugal braking mechanism. The study adopts a Design Failure Mode and Effects Analysis (DFMEA) approach to systematically identify, evaluate, and prioritize potential failure modes and their effects on device functionality and user safety. By implementing DFMEA, this research aims to mitigate risks associated with component failures, structural integrity, thermal stresses, and braking performance, which are critical for controlled descent technology. Key areas of focus include the braking system's ability to maintain a controlled, consistent descent speed under varying load conditions, durability and wear resistance of materials, and response to extreme environmental conditions. Findings from the DFMEA, guides design improvements and operational recommendations, highlighting essential mitigations such as material selection for high wear resistance, redundancy in braking components, and rigorous testing for thermal and mechanical resilience. This comprehensive risk assessment ensures the reliability of the controlled descent device, providing valuable insights for manu-facturers and safety personnel dedicated to advancing the emergency rescue technology.

Keywords: *FMEA, Safety analysis, Risk assessment, Rescue Device*

1. Introduction

Controlled descent devices, especially those utilizing centrifugal braking mechanisms, are essential for ensuring safe evacuation during emergencies from high-rise structures or industrial sites. These devices allow a controlled, consistent descent speed, minimizing the risk of injury due to free fall or abrupt stopping. However, despite their utility, controlled descent devices are subject to several potential risks and failure modes that can compromise safety and device performance. Key risks include brake mechanism failure, material wear and fatigue, overheating, and uncontrolled descent speeds under varying loads. Failures in the centrifugal braking system could result in an excessive descent rate, posing a direct threat to the safety of the descending individual. Additionally, prolonged or repeated use may lead to brake shoe wear, material degradation, and thermal stresses, impacting the device's ability to maintain consistent braking force over time. Environmental factors like moisture or corrosion could also have an adverse impact on the braking performance, increasing the probability of malfunction during emergency use.

To address these risks systematically, different methodologies & techniques are being developed for risk treatment & analysis of any engineering devices, systems and industrial techniques, such as Hazard and Operability (HAZOP) analysis, Job Safety Analysis (JSA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), etc. Among that Failure Modes and Effects Analysis (FMEA) is the most powerful techniques for risk assessment of mechanical engineering systems. The Design Failure Mode and Effects Analysis (DFMEA) approach proves invaluable by allowing engineers to identify potential failure modes at each stage of the device's operation and design, assessing their severity, occurrence probability, and detectability. By prioritizing high-risk failure modes, DFMEA enables the development of targeted mitigation strategies, such as enhanced material selection for high thermal resistance, redundant safety features in the braking mechanism, and preventive maintenance schedules. Through this proactive approach, DFMEA enhances the overall safety, reliability, and robustness of controlled descent devices, making it an essential tool for design optimization and risk mitigation in emergency rescue technologies.

2. Literature Review

A literature review is carried out on risk mitigation strategies for controlled descent device which provides a comprehensive understanding of past research and design challenges associated with emergency rescue systems. By examining prior studies on failure modes, braking mechanisms, and material durability, designers can identify proven methods and emerging technologies that enhance safety and reliability. This synthesis of existing knowledge enables more effective application of tools like DFMEA, guiding innovations that reduce potential risks and improve the performance of controlled descent devices in critical situations. Failure Mode and Effects Analysis (FMEA) is a widely adopted systematic approach used to identify potential failure modes, assess their impacts, and prioritize mitigation actions across various industries. Over the years, the traditional FMEA methodology has undergone significant evolution, incorporating advanced analytical tools, decision-making frameworks, and domain-specific adaptations to address complex modern engineering challenges. This literature review explores a broad spectrum of recent research contributions that enhance the accuracy, applicability, and integration of FMEA with other methodologies such as fuzzy logic, machine learning, multi-criteria decision-making, and reliability-centered maintenance. The studies span diverse fields including automotive, aerospace, energy, manufacturing, and healthcare, reflecting the versatility and critical role of FMEA in improving product design, safety, and system robustness.

Aguirre and P. D. (2021) [1] proposed PFDA-FMEA, an integrated approach designed to improve FMEA assessments during product design, emphasizing enhanced prioritization and evaluation mechanisms. Complementing this, Akhirahmad and N. M. (2019) [2] introduced a Design Failure Mode Effect Analysis combined with a customer approach matrix to address automotive industry challenges, underscoring the integration of customer feedback in failure prioritization. Human-machine reliability perspectives have also been explored, as seen in Amaya-T et al. (2022) [3], who developed a series-parallel approach to improve reliability evaluation in machine tools, demonstrating the importance of system-level integration in FMEA practices. Similarly, Binghan (2022) [4] applied DFMEA specifically to the rotor design of nuclear power stream turbines, highlighting the method's relevance in high-stakes energy systems. Multi-criteria decision-making (MCDM) approaches have gained traction in risk assessment. Chakhrit and B. M. (2024) [5, 6] contributed a hybrid integrated MCDM method tailored for the automotive parts industry, combining quantitative and qualitative data to enhance risk evaluation robustness. This reflects the growing trend to merge FMEA with decision sciences for better accuracy. Dermouche et al. (2022) [7] conducted a qualitative and quantitative reliability analysis of power converters for aeronautical applications, reinforcing FMEA's applicability in aerospace sectors. Dhande (2016) [8] traced the evolution of new product design development using DFMEA, highlighting its transformational role in early design phases. The intersection of FMEA and machine learning is increasingly recognized. Duan et al. (2024) [9] presented an improved FMEA model integrated with machine learning to analyze reliability in intelligent manufacturing systems, signifying the shift towards AI-enhanced failure predictions. Wang (2024) [46] further explored machine learning-enhanced FMEA for risk assessment, establishing the value of data-driven techniques in improving failure mode analysis accuracy.

In aerospace and safety-critical industries, Ehigiato and H. B. (2023) [10] discussed safety and product robustness during air vehicle design, applying FMEA to optimize system reliability under stringent requirements. Fabis-D (2022) [11] focused on risk prioritization within fluid power components via FMEA, broadening the application to hydraulic systems. The integration of DFMEA and PFMEA has been studied by Fasolo et al. (2022) [12], advocating for enhanced co-development of products and production processes, thus ensuring holistic risk management from design through manufacturing. Similarly, Feng et al. (2024) [13] applied fuzzy FMEA models to offshore wind turbines' failure analysis, incorporating uncertainty into risk evaluations. Fuzzy logic applications in FMEA have been detailed by Filo and Fabis-D (2018) [14] and Ghasemi (2023) [15], who used intuitionistic fuzzy environments for personal fall arrest systems, reflecting efforts to handle imprecise failure data. Golkhani and R. G. (2018) [16] combined FMEA with Analytic Hierarchy Process (AHP) to determine critical safety hazards, demonstrating the benefit of hierarchical weighting in risk prioritization. Hendra et al. (2023) [17] employed a DMAIC approach alongside FMEA to assess technical disruptions in commuter electric trains, highlighting the synergy between continuous improvement methodologies and failure analysis. Jayatilleka (2020) [18] emphasized the importance of systems engineering modeling as prerequisites to FMEA, facilitating more structured failure investigations. Novel FMEA frameworks have been introduced by Ju (2024) [19], who used evidential Best-Worst Method (BWM) and SMAA-MARCOS methods to improve failure mode prioritization, indicating a trend towards hybrid analytic methods. Karacan and E. I. (2021) [20] demonstrated machine vision-supported quality control integrated with DFMEA and PFMEA in rotary switch production, showcasing the role of automation in risk assessment.

The evaluation of battery failure modes in electric vehicles has been studied by Kirana and P. N. (2023) [21], underscoring FMEA's critical role in energy storage system reliability. Li Zhaojun and W. G. (2018) [22] utilized text mining for reliability analysis in design FMEA, introducing big data techniques for extracting failure insights. Dependency-based FMEA models were proposed by Liou (2024) [23], addressing complex product risk analysis in power supplies by accounting for interdependent failure modes. Liu (2016) [24] applied FMEA to quality improvements in packaging design for TFT-LCD industry, illustrating its versatility in manufacturing sectors. Ma et al. (2024) [25] combined q-rung orthopair fuzzy cognitive maps with TOPSIS for failure mode analysis, integrating causal relationships into risk evaluation, while Marasch and H. A. (2018) [26] focused on applying DFMEA to improve legacy product producibility. Sustainability considerations have been integrated into failure analyses, as Mesa et al. (2018) [28] introduced sustainability concepts into DFMA for sheet metal enclosures, signaling environmental awareness in design risk management. Battery manufacturing risks were assessed by Masoumbeigi and P. D. (2024) [27], who linked FMEA with cost estimation of accidents versus prevention, bridging risk management and economic evaluation. Naranje et al. (2023) [29] applied FMEA to electric converted vehicles, expanding failure mode analysis to emerging electric transport systems.

Reliability assessments in harsh environments were tackled by Nawghane and V. B. (2022) [30] via physics of failure (PoF) methods combined with FMEA, demonstrating hybrid approaches in sensor module reliability. Özfırat and Ö. M. (2022) [31] evaluated belt conveyor accident risks using FMEA and event tree analysis, emphasizing complementary safety analysis techniques.

Prabir and S. K. (2021) [32] utilized factor analysis to refine Risk Priority Number (RPN) assessments in automobile plants, improving failure prioritization metrics. Rahimdel and G. B. (2021) [33] prioritized failure risks in mining railcars, evidencing FMEA's reach into heavy industry. Rajpathak et al. (2021) [34] introduced a semantic similarity model to augment engineering data with new failure modes in automotive applications, enhancing data-driven FMEA methodologies. Salah et al. (2023) [35] modified FMEA for Industry 4.0 environments, reflecting adaptation to smart manufacturing contexts. Ropero et al. (2023) [36] analyzed reliability based on preventive maintenance of pumping units for oil extraction, showing the integration of FMEA with maintenance strategies. Safety and reliability analysis of butterfly valves in offshore oil and gas were discussed by Sotoodeh and Karan (2022) [37], emphasizing FMEA's role in critical infrastructure. Seiti et al. (2021) [38] developed modified R-numbers for risk-based fuzzy information fusion, enhancing system resilience analysis through FMESRA frameworks. Sellappan and N. D. (2015) [39] evaluated RPN in DFMEA using factor analysis, contributing to methodological refinements. Shafiee (2023) [40] conducted failure analysis on spar buoy floating offshore wind turbines, highlighting environmental factors in failure analysis. Sharma and S. S. (2018) [41] provided an extensive literature review on FMEA implementation, consolidating foundational knowledge and recent advances. Silveira et al. (2023) [42] integrated multiple failure mechanisms into life assessment methods for centrifugal pump impellers, presenting comprehensive risk evaluation approaches. Sini and P. A. (2022) [43] used simulation-based methods to develop hardware failure detection and mitigation algorithms in mobile robots, demonstrating FMEA's role in software-hardware integration. Ullah and B. M. (2022) [44] applied FMEA to hospital rapid response systems to identify and mitigate failures, showcasing healthcare applications. Ünlükal and Ş. M. (2018) [45] combined FMEA with Grey Relational Analysis for risk assessment in plastic injection processes, highlighting multi-method risk evaluation. Xiao and H. H. (2011) [47] addressed multiple failure modes and weighted RPN evaluations, offering refined quantitative analysis techniques. Yang and K. M. (2023) [48] investigated innovation fusion in robust mechanical system design, underlining advanced design methodologies supported by FMEA. Finally, Zhang et al. (2023) [49] conducted reliability prediction and FMEA of loading/unloading truss robots for CNC punching machines, reinforcing FMEA's applicability in automated manufacturing systems. Similar analysis was reported by Babre et al. (2023)[50] and Shinde et al. (2024) [51]. Sarje (2018) performed Monte Carlo simulation for cost effective maintenance tasks for various critical component of the system, identified by Ishikawa diagram and failure mode effect and criticality analysis (FMECA). Bagade et al. (2023, 2014) reported various loading due to wind on turbine blades and special airfoils respectively.

FMEA is a versatile, evolving tool used across various industries, including automotive, aerospace, healthcare, energy, and manufacturing. Its integration with advanced methodologies, such as GANs, fuzzy logic, and hybrid risk assessment methods, ensures its continued relevance and effectiveness in addressing the complexities of modern engineering systems. The **Table 1** shows the various nomenclature used during the study.

Table 1: Nomenclature

Nomenclature	Description
FMEA	Failure Mode and Effects Analysis
FTA	fault tree analysis
RPN	risk priority number
VL	Very Low
L	Low
ML	Mildly Low
M	Medium
H	failure mode and effects analysis
VH	Very High
S	Severity
O	Occurrence
D	Detection

3. Methodology

FMEA process for the rescue device starts with creating with the boundary diagram, which serves as a crucial tool to visualize and define the scope of the system and its interactions as shown in figure 1.

The boundary diagram outlines the key components such as the brake shoes, responsible for generating friction to control descent speed, the retracting springs, which ensure the brake shoes return to their initial position, and the steel wire rope, which acts as the lifeline wound on the brake drum to manage the controlled descent. The diagram highlights the interfaces between these components, including the interaction between the brake shoes and the brake drum, where centrifugal force activates the shoes during descent, and the tension in the wire rope that affects the drum's rotation. Additionally, the diagram considers external factors like the user's weight and environmental conditions that interact with the system. This structured visualization helps identify potential failure modes at the interfaces such as brake shoe wear, spring malfunction, or rope slippage—facilitating a more comprehensive risk assessment and targeted mitigation strategies in the FMEA analysis.

Similar to the boundary diagram the P-Diagram (Parameter Diagram) is used to identify the key factors influencing the system's performance. The P - diagram as shown in Fig. *2* identifies and categorizes the system's inputs, outputs, control factors, noise factors, and the overall function. The power input to the mechanism is generated by means of the force generated due to free falling weight of the system (Human + device) acted upon by gravitational force, which activates the mechanism producing centrifugal force acting on the two brake shoes. Other inputs include the rotational speed of the brake drum and the tension in the steel wire rope, which affects how the system handles the descent speed.

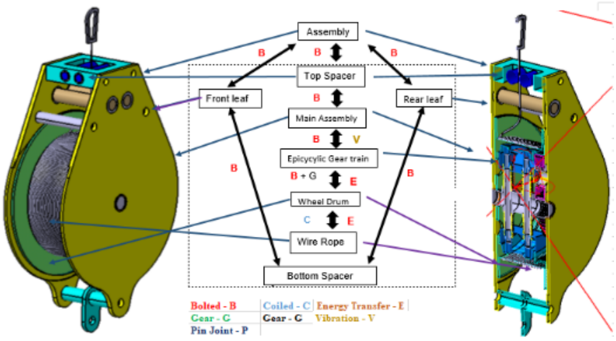

Fig. 1: Boundary diagram

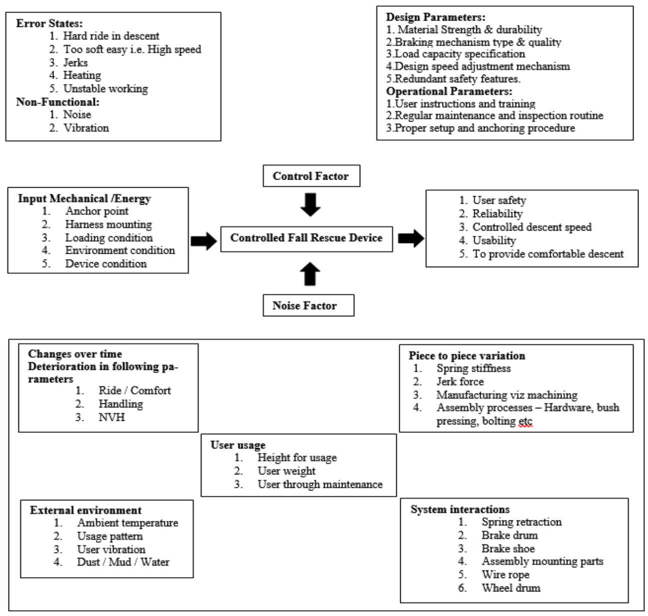

Fig. 2: P - Diagram (Parameter Diagram)

The desired output is a regulated and controlled speed, ensuring a safe and smooth descent. Control factors such as the spring tension (from the four retracting springs), the brake shoe's engagement with the drum, and the material properties of the brake components are essential for ensuring consistent braking performance. Noise factors that can affect the system include environmental changes (like temperature or humidity), wear on the brake shoes over time, and potential contamination of the braking surfaces. By clearly mapping out these parameters, the P-Diagram helps to understand how the system operates under varying conditions and assists in identifying potential failure modes, such as excessive braking due to spring malfunction or insufficient friction, which may result in uncontrolled descent. This structured analysis informs the FMEA, allowing for better identification of risks and the development of effective countermeasures to ensure device reliability and safety.

The sequence followed in the present study as shown in Fig. **3**. The methodology consists of four major steps as below.

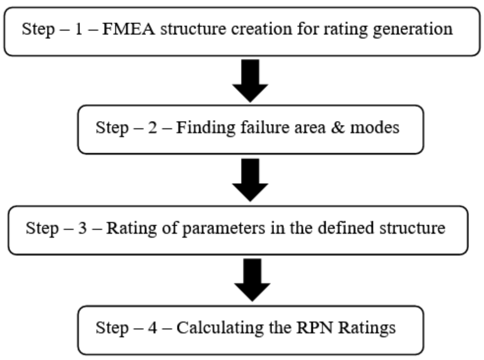

Fig. 3: FMEA - Methodology

Step 1 – FMEA Structure Creation for Rating Generation:
In this step, the framework for the FMEA process as established by identifying the key components and subsystems of the Controlled Fall Rescue Device (CDD). This includes critical elements such as the anchor point, wire rope, harness, descent mechanism, and control systems. Each component is analysed for potential failure modes, and rating scales for severity (S), occurrence (O), and detection (D) are defined. The structure ensures consistent evaluation and prioritization of risks across the system.

Step 2 – Finding Failure Areas and Modes:
Once the structure is defined, potential failure modes and areas of concern for each component are identified. For the CDD, failures such as anchor point detachment, wire rope breakage, harness malfunction, descent speed issues, and operational failures (e.g., stopping mid-descent) are considered. Environmental factors like weather and potential obstacles during descent are also evaluated. This step focuses on systematically listing all possible ways the device could fail during operation.

Step 3 – Rating of Parameters:
After identifying failure modes, each mode is rated based on three parameters: severity (S), occurrence (O), and detection (D). Severity measures the impact of failure, occurrence rates the likelihood of the failure happening, and detection assesses the chances of identifying the failure before it affects performance. For example, failures like anchor point or wire rope failure would receive high severity ratings due to their potential to cause severe injury or death.

Step 4 – Calculating the RPN Ratings:
Finally, the Risk Priority Number (RPN) is calculated for each failure mode by multiplying the severity, occurrence, and detection ratings ($RPN = S \times O \times D$). The RPN helps prioritize which failure modes require immediate attention. High RPN values indicate critical areas where risk mitigation is necessary, such as improving material quality or adding fail-safes for critical components like the anchor point or descent mechanism. This allows for targeted improvements in design and maintenance strategies to ensure device reliability and safety.

4. RPN Calculation

4.1 Developing a standard framework structure for rating FMEA parameters

Performing FMEA using the standard tables, charts & parameter diagram. RPN number requires a framework for rating its parameters, i.e., S, O, and D. As required a 10-point rating scale terms (very low, low, relatively low, medium, relatively high, high, very high) is defined for measuring FMEA parameters.

4.2 Spotting of failure areas or modes

In this step, firstly a detailed sheet is plotted across assembly, sub assembly and component level. Next, the different failure effects on each component are identified by past research & with experienced personnel's and with existing suppliers, manufacturers and importers.

4.3 Evaluation of RPN

For the FMEA traditional approach, the RPN number is used to conduct the risk assessment. The Potential Failure shows the risk factors.

Key Metrics:
Severity (S): Ranks the consequence of failure from 1 (low) to 10 (catastrophic).
Occurrence (O): Likelihood of the failure occurring, ranked from 1 (rare) to 10 (frequent).
Detection (D): Ability to detect the failure before it occurs, ranked from 1 (easy to detect) to 10 (unlikely to detect).
The three factors are all scored from 1 to 10 on the basis of degree. RPN is the product of occurrence, detection, and severity, which is expressed as:
RPN (Risk Priority Number) is calculated as SEV × OCC × DET.
R.P.N = S * O * D
RPN is extensively used in mechanical engineering & its systems analysis, once all elements are being analysed and assessed with a RPN number, corrective majors are assigned & implemented starting from the maximum RPN number to the minimum number. The expectations from the assigned corrective action is to eliminate or reduce most critical area of element where the failure modes are high. RPN number are to be recalculated once the corrective actions are determined and to ensure whether the critical areas and risks have been minimised or how effectively the corrective action is implemented.

4.4 Failure Mode, Causes and Consequences

In the early stage of the study, failure modes of the device were identified. Existing & established rescue device in the market were experienced & users were experimented and interviewed, and failure modes were noted down. The found failure modes their causes, along with and their consequences are reflected in Table-2. Incorrect usage, overuse, no maintenance, and usage of peripheral equipment with low quality are the primary reasons of failure. Moving on in detailed, failure in different parts of the device can cost up to the human life as well.
A systematic FMEA approach identifies the potential failure modes in each component, assesses the severity, likelihood of occurrence, and detection capability, and then calculates a Risk Priority Number (RPN) to prioritize risks. This structured approach enables engineers to proactively address critical issues that could compromise device performance and user safety.

Table 2: Component level FMEA

Component Level Failure Mode Effective Analysis										
Sr. No	1	2	3	4	5	6	7	8	9	10
Part Name	Anchor hook	Wire rope	Harness / Jacket	Housing	Epi- cyclic gear train	brake shoe	Spring mechanism	Axle	Bearings	Connecting Bolts
Part Function	Connects device to anchor point	Supports load	Holds the user securely	Protects internal components	Transmits rotational force	Provides friction for braking	Controls brake engagement	Supports rotating components	Reduces friction in rotation	Secures components together
Potential Failure Mode	Breakage	Fraying or snapping	Tear or failure	Cracking or deformation	Gear tooth breakage	Excessive wear	Loss of tension	Bending or fracture	Wear or overheating	Loosening or shear
Potential Effects of Failure	Device detachment, fall risk	Loss of support, fall risk	User slipping out	Internal parts exposed/damaged	Loss of torque, malfunction	Reduced braking effectiveness	Break not engaging properly	Misalignment, malfunction	Increased friction, breakdown	Component separation
Potential causes of failure	Overloading, corrosion	Wear, improper handling	Wear, improper use	Impact, poor material choice	Misalignment, overload	High friction, overheating	Fatigue, corrosion	Overloading, fatigue	Overloading, poor lubrication	Vibration, overloading
Existing Current Controls	Regular load testing	Visual inspections	Material testing, inspection	Shock testing	Load testing, alignment checks	Heat-resistant materials	Pre-tension checks	Load testing	Regular lubrication checks	Torque checks, Loctite

conditions	Occurrence (O)	3	4	2	3	2	4	3	3	4	3
	Severity (S)	9	10	8	7	8	9	8	8	7	8
	Detection (D)	4	3	3	4	4	3	3	4	3	3
RPN	Risk Priority Number (O*S*D)	108	120	48	84	64	108	72	96	84	72
Recommended actions & status		Use stronger materials, inspect regularly	Use higher quality rope, check tension	Use durable materials, enforce weight limits	Use impact-resistant materials	Improve alignment, monitor load	Use high-wear materials, add cooling	Use corrosion-resistant material	Use stronger alloy, regular inspection	Improve lubrication schedule	Add lock washers, increase inspection frequency
Resulting RPN	Actions taken	Strengthened materials	Upgraded rope quality	Reinforced design	Material upgraded	Alignment improved	Added cooling fins	Material updated	Alloy upgraded	Lubrication improved	Lock washers added
	Occurrence (O)	2	3	1	2	1	3	2	2	3	2
	Severity (S)	9	10	8	7	8	9	8	8	7	8
	Detection (D)	3	2	2	3	3	2	2	3	2	2
	Risk Priority Number (O*S*D)	54	60	16	42	24	54	32	48	42	32

Occurrence (O), Severity (S), and Detection (D) are rated from 1 (low) to 10 (high).
Risk Priority Number (RPN) is calculated as $RPN = O \times S \times D$.
Recommended Actions were suggested based on identified failure modes to reduce the RPN.
In an FMEA analysis, each component's current controls are listed as existing preventive measures, such as material testing, inspections, or routine maintenance schedules. These controls serve as baseline methods for managing risks associated with potential failures. However, as part of the FMEA process, if the calculated RPN for any failure mode is high, it signals a need for additional mitigation actions to reduce the risk. The Actions Taken column in the FMEA documents the specific measures implemented based on this analysis, such as upgrading materials, reinforcing components, or adjusting inspection frequency.
The difference between Current Controls and Actions Taken highlights how FMEA provides targeted guidance for engineers. For instance, if brake shoe wear identified as a high-risk failure mode despite current heat-resistant materials, engineers may respond by using advanced wear-resistant materials. By systematically addressing each risk, FMEA helps in refining the design and improving reliability, ultimately ensuring the rescue device is safer, more durable, and better suited for emergency scenarios. Thus, FMEA is used as a improvement tool, guiding engineers to develop robust, fail-safe rescue devices by methodically reducing risks in line with real-world performance demands. Here is the FMEA results table for the risk assessment of the Controlled Fall Rescue Device based on the information, which is processed. The RPNs values of the different failure modes based on processed information and data is mentioned in table 3 along with the focus areas for respective failure mitigation.

Table 3: Failure Mode and RPN Value results

RPN value results								
Failure Mode (FM)	**Failure Description**	**Potential causes of failure**	**Severity (S)**	**Occurrence (O)**	**Detection (D)**	**RPN = (S*O*D)**	**Mitigation Focus**	**Consequence of failure**
FM1: Anchors point failure	Failure of the anchor point	Using weak structures as the anchor point	9	2	3	54	High-quality materials, frequent inspections	User death
FM2: Wire rope failure	Breakage or wear of the wire rope	Rope abrasion, rope life, improper maintenance, purchasing inexpensive low-quality equipment	9	2	3	54	Regular testing, use of durable materials	User death
FM3: Harness failure	Failure of the harness during use	sewing quality, Improper maintenance, using low quality	9	2	4	72	Redundancy in design, routine checks	User death
FM4: Mechanism failure	Mechanical failure in descent mechanism	Improper maintenance, fatigue life	7	5	4	140	Design improvements, enhanced maintenance	User death
FM5: Descent speed failure (over speed)	Uncontrolled descent speed	Mechanism dis function, Gear Jam	8	5	3	120	Precise control systems, fail-safes	Severe injury, death is possible
FM6: Operational failure (hanged in between)	Device stops during descent	Mechanism dis function, Gear Jam	8	4	4	128	Ensure continuous operation, emergency release	User hanged in between
FM7: Obstacle failure (hitting during descent travel)	Collisions with obstacles during descent	Incorrect descent method & Location	7	5	3	105	User training, obstacle detection systems	Severe injury, death is possible

FM8: Environment failure	Adverse environmental conditions (weather, etc.)	Non visibility, Wetness, Max temperature, Dust & sand	7	5	3	105	Weather protection, environmental testing	Severe injury, death is possible
FM9: Operational failure	Operational malfunction during use	Lack of training, incorrect use of device, no emergency procedures.	7	4	4	112	Frequent testing, user training	Severe injury, death is possible

In comparison of high and low RPN value such as, FM6: Operational failure i.e. Hanged in between is having the lowest RPNs. Focusing with RPNs higher than 125 number that failure modes are identified as critical and is focused majorly. Values of occurrence, detection, and consequence recorded on the research-based approach are plotted as shown in Fig. **4**. with comparative values for all failure modes versus the given ratings.

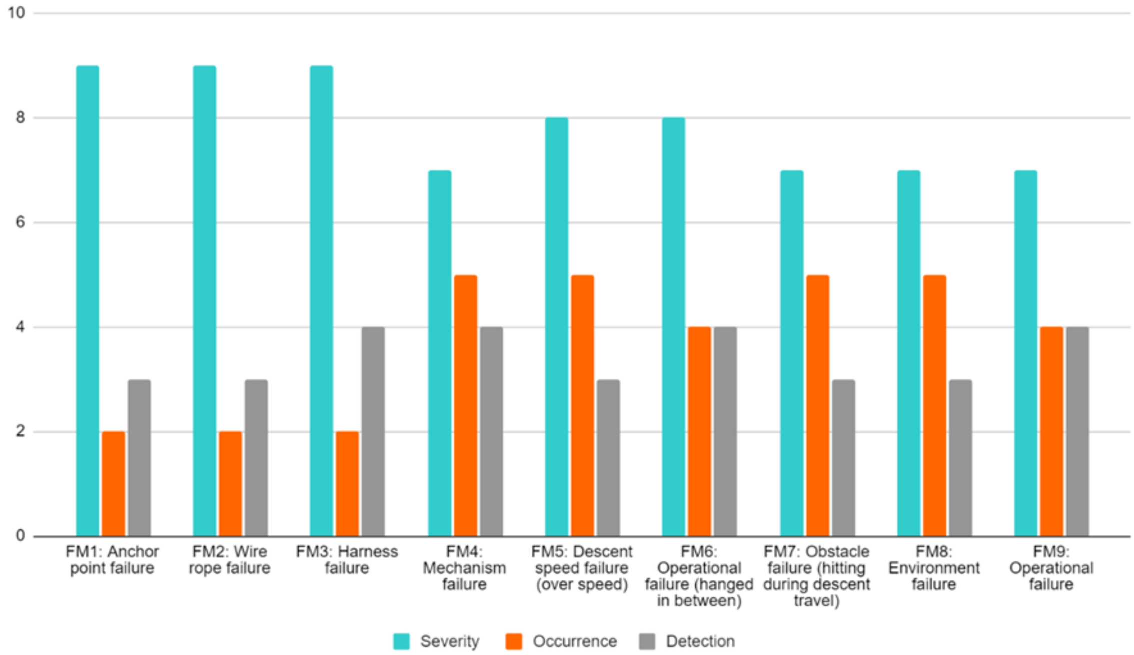

Fig. 4: Severity, Occurrence and Detection

5. Results and Discussion

In the FMEA study, we have analyzed critical components of a controlled fall rescue device, focusing on the centrifugal braking mechanism, wire rope, harness, anchor points, and control systems. The goal was to identify potential failure modes, prioritize them using the Risk Priority Number (RPN), and propose mitigation strategies. Similar studies have indicated that braking mechanisms and descent speed control are high-risk areas in safety devices, demanding attention to material selection, design redundancy, and regular maintenance checks [3, 4]. These improvements are critical for ensuring reliable performance of rescue systems in emergency situations. Table 4 shows high RPN analysis with respective mitigation strategies.

Table 4: High RPN Area Analysis

Sr.No	Failure Mode	RPN Value	Suggested Mitigation
1	FM4: Mechanism failure	140	- Use hardened alloy materials to reduce wear. - Employ lubrication systems to minimize friction. - Schedule routine preventive maintenance. - Incorporate dual brake systems for redundancy.
2	FM5: Descent speed failure	120	- Install redundant speed governors for precise control. - Apply electronic braking systems for reliability. - Conduct regular sensor calibration. - Introduce automatic override for over speed detection.
3	FM6: Operational failure	128	- Install backup braking mechanisms. - Provide redundant power sources. - Integrate manual release options for emergencies. - Implement error detection algorithms.
4	FM9: Operational malfunction	112	- Conduct regular diagnostic testing. - Ensure backup communication systems for alerts. - Provide extensive user training. - Install real-time monitoring systems for system health feedback.

As shown in Table 3. The mechanism failure (FM4), with the highest RPN value of 140, highlights the need for enhanced material selection, regular maintenance, and redundant systems to mitigate the risk. Literature on personal fall systems suggests that hardened materials and advanced manufacturing techniques improve the reliability of braking systems in emergency devices [3, 5, 6]. Descent speed failure (FM5),

with an RPN of 120, emphasizes the necessity for multiple speed governors and precise braking controls to avoid uncontrolled falls, as recommended in similar safety-critical systems [4, 6]. The operational failure (FM6) shows an RPN of 128, indicating the need for continuous operation and backup systems to prevent malfunctions during critical descent periods [6, 8].
The concerned consequence ratings are discussed as below.

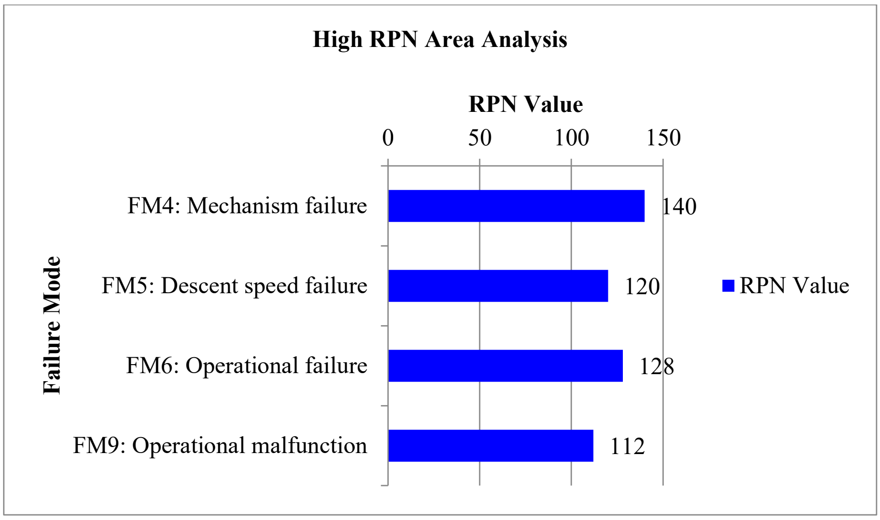

Fig.5: High RPN Analysis

Here is the graph in figure 5 showing the **Risk Priority Numbers (RPN)** for high-risk failure modes in the controlled fall rescue device. The horizontal bar chart makes it easy to compare and prioritize the failure modes based on their RPN values.

a) **High Consequence Failures:**

i. **FM1: Anchor Point Failure**, **FM2: Wire Rope Failure**, and **FM3: Harness Failure** all have high consequence ratings (9). These components are critical for user safety as their failure could lead to severe injury or death. Ensuring the reliability and robustness of these components should be a top priority.

ii. **FM5: Descent Speed Failure (Over Speed)** and **FM6: Operational Failure (Hanged in Between)** also pose significant risks (consequence ratings of 8). Control mechanisms must be precise, and fail-safes should be incorporated to manage descent speed effectively and ensure continuous operation.

b) **Moderate Consequence Failures:**

i. **FM4: Mechanism Failure**, **FM7: Obstacle Failure (Hitting During Descent Travel)**, **FM8: Environment Failure**, and **FM9: Operational Failure** all have moderate consequence ratings (7). These failures can still result in serious incidents but are somewhat less critical than the high consequence failures. Improvements in design, user training, and environmental protection measures can mitigate these risks.

c) **Occurrence and Detection Ratings:**

i. Failures such as **Mechanism Failure (FM4)**, **Descent Speed Failure (FM5)**, **Obstacle Failure (FM7)**, and **Environment Failure (FM8)** have higher occurrence ratings (5), indicating these issues are more likely to happen. These areas need more robust preventative measures and better design controls.

ii. Detection ratings for many failure modes are around 3-4, suggesting that while current detection mechanisms are in place, there is room for improvement. Enhanced monitoring, more frequent inspections, and advanced detection technologies could help reduce these ratings.

d) **Focus Areas for Improvement:** The key focus areas for improvement in a rescue device are related to critical components like the anchor point, wire rope, and harness, as well as the control mechanism reliability and environmental challenges. To enhance safety and performance, it is essential to regularly test these critical elements, use superior materials, integrate redundancy, and design the device to account for environmental factors and obstacles. Advanced controls, maintenance routines, and real - world testing under various conditions can help mitigate risks and improve the overall reliability of the system;

e)

f) **Table** 5 shows the areas, which needs to be focused, and its corresponding recommendations for improvement.

Table 5: Areas of improvement

Sr. No	Focus Area	Issue / Concern	Improvement Recommendations
1	Anchor Point, Wire Rope, Harness	Critical components with severe failure consequences, though failures are infrequent.	Regular testing, use of high-quality materials, and redundancy in design for safety
2	Control and Mechanism Reliability	Ensuring reliable descent speed control and overall mechanism functionality is crucial.	Implement advanced control systems, fail-safes, and schedule routine maintenance.
3	Environmental and Obstacle Considerations	Risks from adverse weather and obstacles during descent.	Test the device in various environments, including adverse conditions, and account for obstacles.

6. Findings and Conclusion

The findings of this study directly address the core research questions regarding the identification of critical failure modes, evaluation of associated risks, and strategies for enhancing the reliability and safety of a Controlled Fall Rescue Device (CFRD) that utilizes a centrifugal braking mechanism.

The FMEA approach enabled a systematic evaluation of potential failure modes across key components, including the centrifugal brake mechanism, wire rope, harness, anchor points, and control system. Each failure mode was assessed in terms of its severity, likelihood of occurrence, and detectability—quantified using the Risk Priority Number (RPN).

Among all components evaluated, the braking mechanism failure (RPN 140) and uncontrolled descent speed (RPN 120) emerged as the most critical risks, indicating a significant threat to operational reliability and user safety. These failure modes highlight the need for robust mechanical design, reliable speed control, enhanced material resistance to wear, heat, and environmental exposure.

Other notable findings include:

- Operational failure (RPN 128), pointing to the risk of system-wide malfunction due to power loss or component miscommunication.
- Operational malfunction (RPN 112), underscoring the importance of proper diagnostics, monitoring systems, and user handling.

The study also found that wear and fatigue in the brake shoes, thermal degradation, and moisture or corrosion were contributing factors that could impair consistent braking performance over time. These findings suggest that mitigation strategies such as using thermally stable and corrosion-resistant materials, installing redundant braking and speed governor systems, and developing real-time condition monitoring can significantly reduce failure likelihood.

Furthermore, the DFMEA analysis reinforces the role of design-stage interventions, such as the inclusion of manual override mechanisms, fail-safe designs, and sensor calibration protocols, in proactively addressing high-risk scenarios.

While the FMEA proved effective in prioritizing risks and suggesting design improvements, the study also acknowledges limitations—particularly the lack of real-world failure data and the need for more extensive environmental testing under varying operational conditions. These gaps suggest that future studies should include long-term field data, stress-testing under harsh conditions, and evaluations of sensor-based detection systems to enhance failure predictability and early response capabilities.

In summary, the findings confirm that:

- Braking system reliability and descent speed regulation are the most critical factors for ensuring user safety.
- Material choice, system redundancy, and proactive monitoring are central to mitigating identified risks.
- Ongoing testing and real-world data integration are essential to evolving the current design into a safer, more dependable rescue solution.

These insights align with the original research objectives and provide a roadmap for the continued development and risk mitigation of controlled descent rescue devices in emergency applications.

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