Human-centered Design and Musculoskeletal Risk Evaluation for All-terrain Hybrid Electric Vehicle: A RULA and REBA Approach

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Human-centered Design and Musculoskeletal Risk Evaluation for All-terrain Hybrid Electric Vehicle: A RULA and REBA Approach

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Abstract: Global trends are towards EV or HEV to reduce emissions from fossil fuel which leads to global warming. In ally to this ongoing effort, the work aims to retrofit an existing All-terrain vehicle (ATV) powered by an IC engine to a series and parallel split hybrid electric vehicle incorporating both of the drive configurations. In the initial stage, the primary focus has been on the design and analysis of the chassis which involved reconfiguring the chassis of an ATV to accommodate all additional components required for a HEV retrofitted from IC drivetrain. To ensure the safety of occupants and the components during collision and rollover, the chassis acts as a strong structural support enabling an optimized space to ensure smoother interconnectivity of various components. With safety as a prime parameter, the chassis also contributes to the aesthetic appearance of the vehicle. Consequently, a comprehensive analysis of the chassis was performed, considering various impact scenarios such as front, rear, side impacts, rollovers, and drop tests, as well as evaluating its bending characteristics and torsional rigidity. A weighted point Material Selection approach has been adopted to ensure chassis sustainability. An ergonomic assessment was performed to ensure the design suitability for human posture in handling several operations in diverse dynamic conditions. The advanced RULA and REBA approach is used to diagnose Musculo Skeletal Disorder with the help of Manikin functions that ensure faster-driven dimensioning with high accuracy. This study provides valuable insights into ATV design by optimizing structural performance and ergonomic comfort, ultimately enhancing driver safety and reducing the risk of musculoskeletal disorders. The findings contribute to the development of high-performance ATVs with improved maneuverability and human-centric design.

Keywords: Hybrid Electric Vehicle; Retrofit; Ergonomics; RULA and REBA; Manikin

1. Introduction

In response to the global imperative to reduce emissions from fossil fuels and combat the detrimental effects of global warming, the automotive industry is witnessing a significant shift towards Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). This transition is driven by the urgent need to curtail greenhouse gas emissions and promote sustainable transportation solutions[1]. In this context, the present work endeavors to address this critical need by embarking on the ambitious task of retrofitting an existing ATV work on Fossil Fuel into a Hybrid Electric Vehicle (HEV), aligning with the prevailing global trend[2-4]. The initial phase of this comprehensive retrofitting project focuses primarily on the redesign and analysis of the vehicle’s chassis[5]. The chassis stands as a fundamental element within the vehicle’s architecture, serving as a structural cornerstone that integrates and harmonizes the functioning of various subsystems[6]. Its significance extends beyond structural integrity; the chassis also influences the vehicle’s aesthetic appeal and plays a crucial role in ensuring occupant safety in the event of collisions or rollovers[7]. To cater to the demands of transforming a conventional BAJA vehicle into a Hybrid Electric Vehicle, substantial modifications to the chassis are essential to accommodate the additional components required for hybridization[8]. Consequently, a comprehensive analysis of the chassis is imperative, encompassing diverse impact scenarios such as front, rear, and side impacts, rollovers, and drop tests, as well as the evaluation of its bending characteristics and torsional rigidity[9]. These assessments are pivotal in ensuring the safety and durability of the retrofitting endeavor, aligning with the weighty responsibility of minimizing environmental impact[10]. The selection of materials for the chassis is a critical decision, given its direct influence on the vehicle's performance and safety[11]. In the context of an All-Terrain Vehicle, which the BAJA vehicle represents, material selection assumes even greater significance[13]. The chosen materials must exhibit qualities such as rigidity, compactness, ergonomic suitability, and cost-effectiveness[12,13]. This underscores the importance of adopting a precise methodology i.e., the Weighted point Material Selection approach for material selection, particularly considering the dynamic challenges that the vehicle will encounter[13,14]. As part of the retrofitting process, the vehicle's chassis is subjected to a battery of impact tests, including front and side impact tests, side bump tests, roll-over impact tests, and torsional rigidity tests[3,4]. Rather than relying solely on destructive testing, the use of Computer Aided Engineering (CAE) software and non-destructive testing methods is integral to comprehensively analyzing the vehicle's performance under dynamic conditions. Several researchers have employed an optimal design for the body profile of a torpedo-shaped Autonomous Underwater Vehicle and a multi-objective optimization scheme based on the optimization algorithm Non-dominated Sorting Genetic Algorithm-II[16]. Advanced methodologies and parametric software tools are employed to ensure ergonomic compatibility by evaluating human posture during various dynamic conditions, a facet crucial for vehicle design[12,15,20]. M Gadola and D Chindamo[19] have covered the formula SAE event and explained the structure of competition in their literature and the author also covers how effective learning helps students enhance their skills. Reza Kashyzadeh. et al.[21] inferred the used FEM as raw data for MLF-type neural network training to achieve the mathematical models that were used as conflicting objective functions for multi-objective optimization of the projectile tip. Patil Lalit and Khairnar H P[26] investigate the human safety of the electric vehicle[22-27]. observed the Musculo Skeletal Disorder (MSD) at an automobile workshop and studied factors affecting and its severity on workers' body parts. Review on green human resource management done in literature[28,29].

This research work aims to retrofit an all-terrain IC Engine vehicle into a Hybrid Electric Vehicle. Reviewing the existing literature, it becomes evident that the retrofitting of All-Terrain Hybrid Electric Vehicles has not yet been explored extensively, highlighting the novelty and significance of this endeavor. Moreover, the ergonomic analysis of human posture during vehicle operation has revealed certain gaps in existing research. Ergonomics analysis for ATV drivers needs to be studied and evaluated. To address these gaps and enhance the precision of physical or dimensioning, advanced Manikin functions are employed to expedite dimensioning processes while ensuring accurate outputs. This facilitates a more comprehensive analysis of Musculo Skeletal Disorders (MSDs) associated with human posture.

2. Methodology

The initial stages of the work progress towards the study of existing IC-powered vehicular configurations of ATVs and the components contributing to the transmission and dynamics of the vehicle Fig. 1. In order to examine the latest evolutions in the field of HEVs and EVs a thorough literature survey has been conducted. From a theoretical standpoint, it is possible to convert any IC-powered vehicle into an electric vehicle, provided the necessary financial resources and technical expertise are available.

Most of the Recent work reveals an understanding of the structure, dimensions, sustainability, and other pertinent parameters related to traditional ATV chassis.

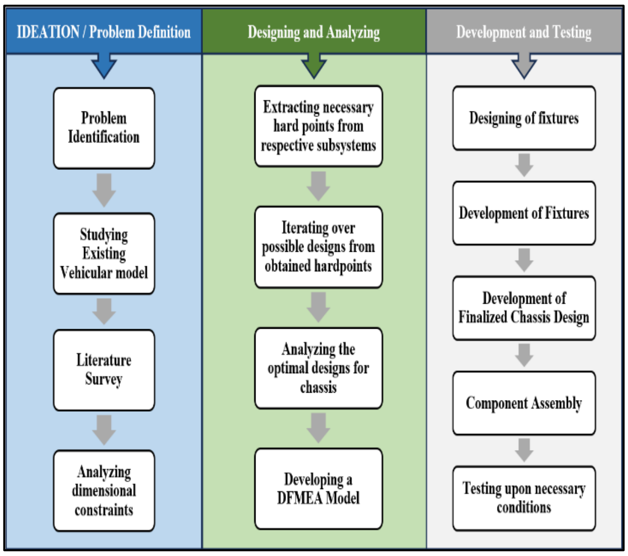

Fig. 1: Methodology implemented.

This analysis facilitated the identification of research gaps in areas such as Design and Development, Modelling, Simulation, Evaluation, Structural Considerations, and Optimization. The design process primarily revolved around developing a chassis suitable for a hybrid electric vehicle. The redesign and analysis of the existing chassis were undertaken with the objective of achieving a compact and lightweight structure for the HEV. The chassis assumes the critical role of providing the necessary strength to support different vehicle components and payload, contributing to the overall rigidity and stiffness of the vehicle. Consequently, the chassis also plays a vital part in the vehicle's security system, necessitating a well-designed chassis to ensure vehicle safety, performance, and rolling resistance. Essential hard points were obtained from respective subsystems to guide the design of the actual chassis. The conceptual design was thoroughly analyzed with respect to various parameters. A Design Failure Mode and Effects Analysis (DFMEA) model was developed to assess potential failure modes and causes, ensuring that the designed products fulfill their intended functions and meet user requirements. The finalization phase aimed to incorporate all necessary changes and obtain final approval, verifying that all design specifications were successfully integrated. Subsequently, the design and development of a new fixture for the chassis were undertaken to accurately hold and support components during the machining process. The CAD model was prepared using CATIA V5 commercial parametric software, and subsequent structural analysis was conducted using ANSYS 2021 R2 commercial CAE software. The development of the chassis involved designing a new chassis specifically tailored for electric vehicles, incorporating aspects such as ergonomics, security, ease of fabrication, and reliability into the design specifications. Rigorous analysis was performed on the key components to optimize strength and rigidity, enhance vehicle components, minimize complexity, and reduce manufacturing costs. For analysis purposes, 3D models were created utilizing SolidWorks software, enabling a comprehensive understanding of the vehicle's mounting requirements. The assembly of all vehicle components was carried out and subjected to rigorous testing to ensure compliance with necessary conditions.

3. Design and Analysis

3.1 Chassis design (Traditional ATV)

The available chassis was developed specifically for conventional internal combustion (IC) engines. The major components constituting the sprung masses included the engine, continuously variable transmission (CVT), gearbox, steering components, and other relevant parts. To ensure optimal performance and stability, the suspension geometries needed to be adjusted in accordance with the masses of these components, thereby maintaining a favorable center of gravity[32,33]. Figure 2 and Figure 3 show the rear and side views of the ATV.

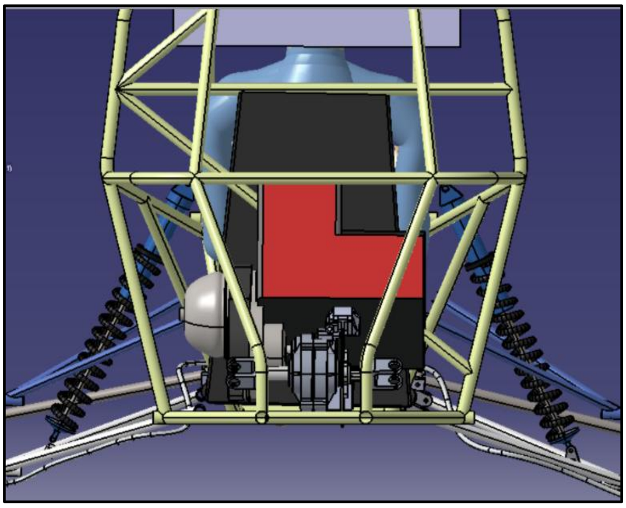

Fig. 2: Transmission assembly rear view of ATV.

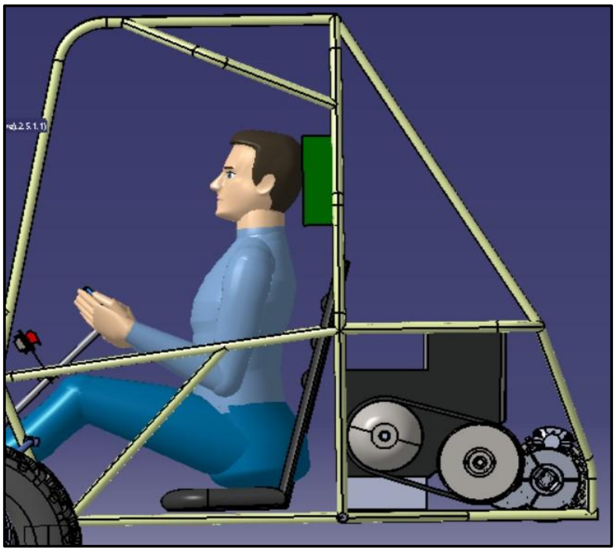

Fig. 3: Transmission assembly side view of ATV.

3.2 Retrofitted chassis model

Retrofitting a chassis begins with two conceptual drivetrain configurations, the first involves the employment of a Planetary gearbox to synchronize the operations of the internal combustion (IC) engine and the electric motor. This concept, although complex, presented challenges in terms of efficiency and safety. As a result, commercial hybrid electric vehicle manufacturers have discontinued the use of this design. The second concept, on the other hand, employed two Brushless DC (BLDC) hub motors, which proved to be an effective solution. Control over the vehicle was achieved through electronic controllers, enhancing operational efficiency. While BLDC hub motors are relatively expensive, their arrangement for retrofitting in a conventional vehicle is straightforward and space-efficient.

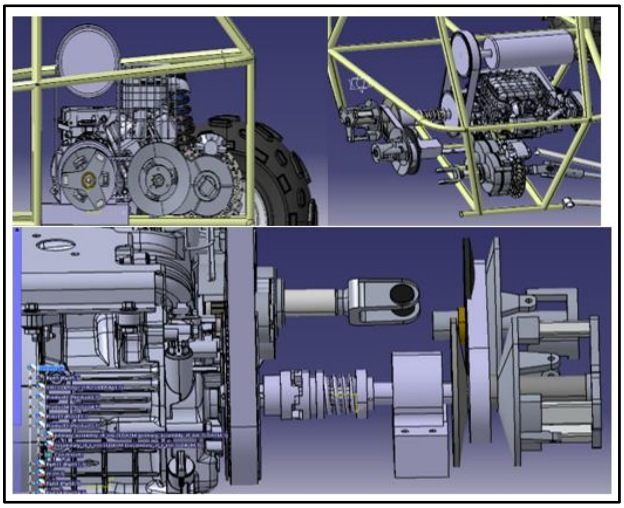

Fig. 4: Drivetrain arrangement used in HEV.

In cases of ATVs power, safety and serviceability are most important. Taking into account the above factors, the second concept utilizing BLDC hub motors was ultimately selected and finalized. In this design, the front wheels are driven by the two BLDC hub motors, while the rear wheels are powered by the IC engine. This configuration strikes a balance between efficiency, ease of retrofitting, and space utilization for an optimized retrofitting process[17,18], optimized layout of HEV shown in Fig. 6.

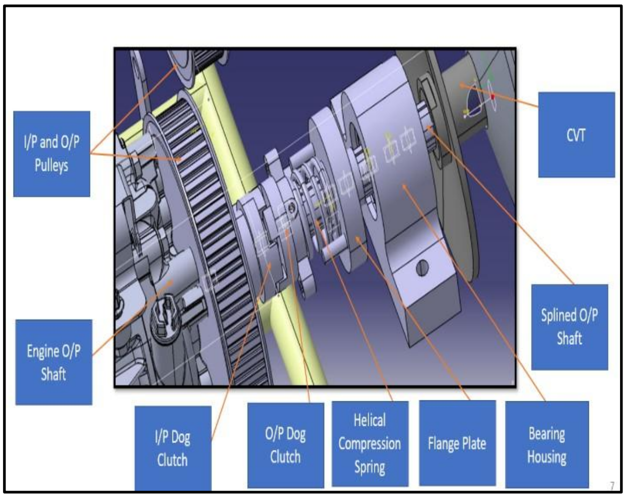

Fig. 5: Transmission assembly model for HEV.

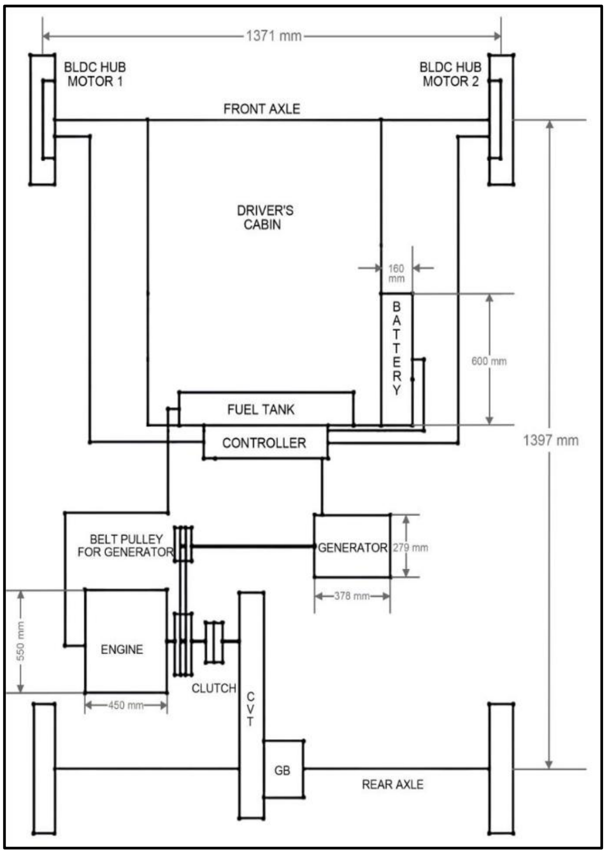

Fig. 6: Layout for HEV.

Figure 4 gives the arrangement of components placed in the HEV. The transmission model and drivetrain arrangement model are shown in Fig. 5. Which need to be considered while designing and analyzing chassis. The components involved in the drivetrain majorly contribute to chassis calculations for overall stability and driver comfort.

3.2.1 Material selection

The weighted-point technique focuses on characteristics and accordingly chooses the key parameters and weight applied to each one based on how significant it performs as a whole. The performance score given to each parameter has been multiplied by the category's weight. The final score for each provider is calculated by the addition of all these categories. The final rating for each provider is calculated by adding together these items. This approach has unique potential to incorporate qualitative and quantitative performance factors. The proposed method has been versatile because it enables the designer to modify the weights specified for each performance area or the performance categories based on the tactical priorities of the design[13,31]. K. Reza Kashyzadeh et al.[26] have experimentally investigated the best material for manufacturing the steering knuckle. To enhance the accuracy of the material selection approach the individual material properties were selected from Ansys granta material properties library and are shown in Fig. 7. The weight assigned to each parameter according to key performance is shown in Fig. 8.

According to the weight point index method, AISI 4130 was found to be the most suitable material chassis for HEV. The next section covers the analysis of chassis for the various dynamic conditions for vehicle safety.

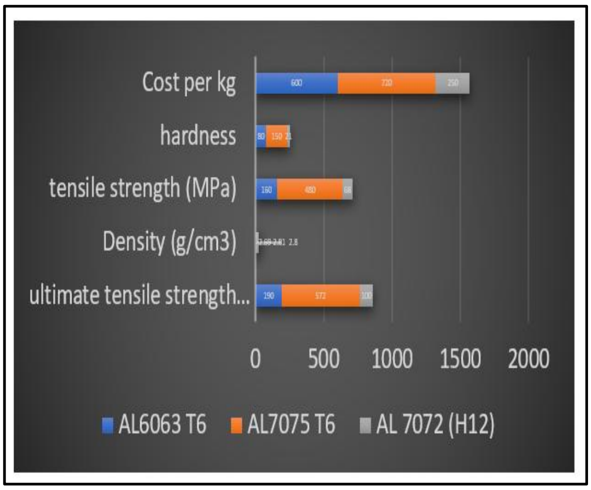

Fig. 7: Material properties considered.

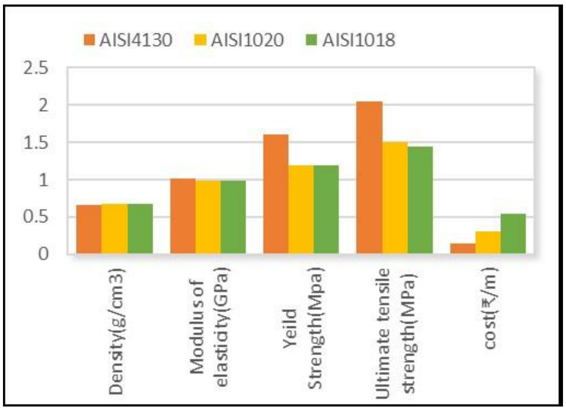

Fig. 8: Weight assigned to material properties.

3.2.2 Bending stiffness and vehicle model parameters

Bending Stiffness for hollow pipes with 25.4 mm varying thickness was calculated as the product of modulus of elasticity for AISI 4130 i.e., 210 GPa and moment of inertia as observed in Fig. 9. The Cross Sections Shortlisted were 1.5, 2, and 2.5 mm. Through a market Survey, it was found that the above-mentioned pipe diameters were available in the following thicknesses i.e., 1.65,1.8,2. Since a cross-section with 25.4 mm × 2 mm gives an optimum weight while maintaining the conditional parameters, it was selected for the primary members. The vehicle parameters such as Height, Tract width, wheelbase, Ground clearance, etc. are tabulated in Table 1 and Fig. 10 shows pipe ID V/s bending stress for various pipe thickness.

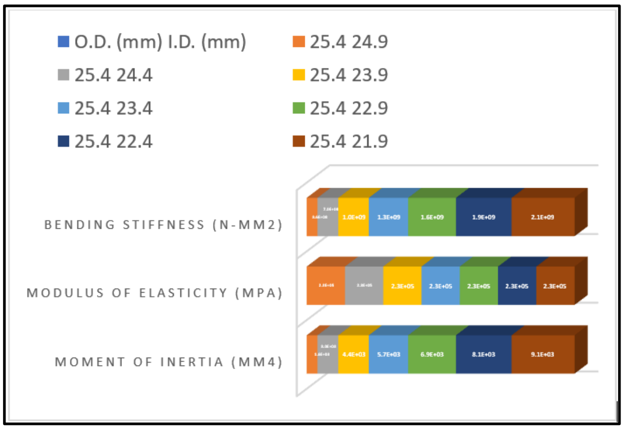

Fig. 9: Bending stiffness for various thickness.

Table 1. Values assigned

Parameter	Value Assigned
Height	1650.924mm
Track width	1371.6
Wheelbase	1397
Ground clearance	355.6
Tire size	23*7-10
Suspension type	Independent suspension
Braking System	Hydraulic

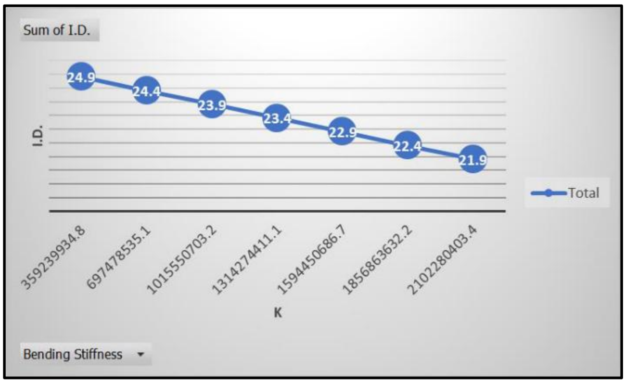

Fig. 10: Graph showing thickness vs bending stiffness.

3.2.3 Force calculation for impact analysis

Force calculation for various impact tests covered in this section with impact analysis results are tabulated in Table 2.

3.2.3.1 Front Impact Analysis

It has been considered the total mass of the vehicle along with the driver around 250kg for the front side and maximum velocity is 18m/s and the time of impact is taken to be 0.15s with an acceleration of 120 m/s^2 which ultimately takes up the force of 30KN. A uniformly distributed 30KN load was imposed on the front bracing members, keeping rear suspension points as fixed support.

3.2.3.2 Rear Impact Analysis

The total mass of the vehicle along with the driver is 350kg considered maximum velocity is 18m/s and the time of impact is taken to be 0.15s with the acceleration of 120m/s^2 which ultimately takes up the force of 30KN. Similar to the frontal impact, a uniformly distributed load of 30KN on the rear members was imposed with suspension points as fixed support.

3.2.3.3 Side Impact Analysis

For side impact, additional momentum comes into the picture since the side opposite to the side of impact won't be fully constrained. Due to this momentum, the time of impact taken was 0.3 seconds. It is assumed that the mass of the vehicle along with the driver is 350kg and the maximum velocity is 18m/s which is the final velocity with acceleration of 120m/s^2. The load of 15KN is applied on the Side Impact Members and on the Lower Frame Side Members.

3.2.3.4 Rollover Analysis

The ATV needs to be designed and validated for the most extreme off-road conditions including a complete rollover. Ultimately the chances of a roll-over are very high. This test needs to be performed with utmost care since the driver should be safe in this extreme condition. The load acting on the vehicle during a roll-over condition is obtained by considering 25 % of the load acting on the front impact. The force of 7.5KN is uniformly distributed along the negative Z-Axis on the top 4 members of the roll cage. The suspension mounting points are assumed to be fixed supports.

3.2.3.5 Side Bump Analysis

The vehicle may experience a bump force on either of its side. This might happen when there is heavy reaction force and the damper is not able to sustain it. Greater forces may lead to a side flip of the vehicle. The general weight distribution of the vehicle is to be 42% - 58% (Front: Rear). Hence, the forces are in the same proportion. front impact force = 12.6KN, while Rear impact force = 17.4KN. The forces are applied in the negative Z direction at the suspension mounting points and the suspension points on the opposite side are kept as fixed points. The vehicle experiences a torsional moment when passing through offroad conditions. Along with this front and rear bump analysis has been carried out.

3.2.4 Load impact investigation

ANSYS 2021 R2 Workbench was used for chassis analysis and tested for various impact tests like Front, Rear, Side-impact, and Rollover analysis along with side, rear, and front bump. Results are tabulated in Table 2 helps in selecting a suitable chassis model for final assembly and development.

Von-Misses Stress, Deformation, and Factor of Safety are the parameters from which a decision on structural performance is carried out. Stresses and deformation on the possessed model are under permissible limits in which the design is safe for most of the dynamic impacts.

Table 2. Results of impact analysis.

Sr. No.	Test	Von Mises Stress (MPa) (a)	Deforma-Tion (mm) (b)	FOS (c)	Safe/ Unsafe
1	Front Impact	224.76	1.53	2.70	Safe
2	Rear Impact	393.85	5.46	1.54	Safe
3	Side Impact	331.18	5.17	1.83	Safe
4	Rollover Impact	72.29	1.13	8.4099	Safe
5	Torsional	300.26	4.467	2.024	Safe
Overall, FOS= impacts FOS/Number of Impacts = 2.86					

The selection of cross-section and proper material resulted in a lightweight chassis with about 30% optimization from the previous versions. Weight distribution aspects were considered and are satisfied for various dynamic conditions.

4. Ergonomics

In the contemporary era of technological advancement, product optimization extends beyond mere functionality to encompass human-centric design principles[34,35]. Design engineers increasingly emphasize the ergonomic integration of operator posture as a critical determinant of product efficacy and safety. In this context, ergonomics serves as a pivotal factor in product development, ensuring biomechanical compatibility and minimizing musculoskeletal strain[30]. To quantitatively assess and optimize operator posture, advanced ergonomic evaluation tools such as Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) are employed. Figure 11 and Figure 12 illustrate the actual manikin posture along with the different viewpoints employed in operating the designed retrofitted chassis. The assessment provides a scientific basis for identifying and mitigating ergonomic risks while promoting optimal and safe working postures.

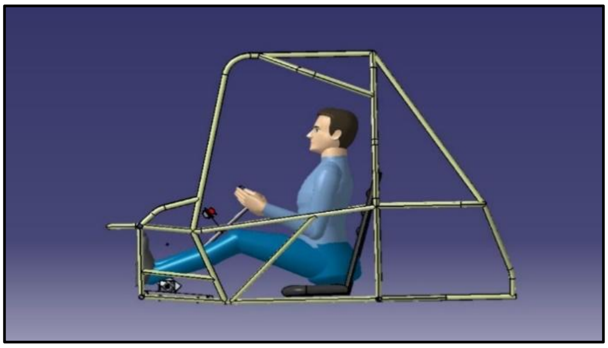

Fig. 11: Human posture

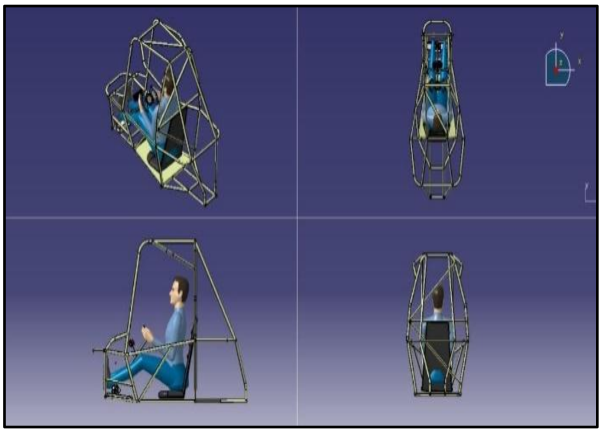

Fig. 12: Various views of ergonomic considerations by manikin.

4.1 Rapid Upper Limb Assessment (RULA)

RULA comprises several human postures confined to the upper limb stating the extremities adhered to the angular position and posture of the body.

Table 3. RULA action level table.

Score	Level of MSD Risks	Actions
1-2	Negligible	No change necessary

3-4	Low risk	May be change
5-6	Medium risk	Investigate, Change further
6+	Very High risk	Implement Change

Figure 19 shows the detailed procedure followed in accessing the positional parameters of a human posture in the designed chassis. A detailed description of different positions considered according to RULA is pic tabulated in Fig.13. The positional parameters of the upper limb were extracted through CATIA V5 software utilizing the Ergonomic Design and Analysis tool in which the Manikin of the actual dimensions was positioned in the designed retrofitted chassis. The positional parameters thus extracted are then utilized to access the risk-associated scores in the RULA worksheet Fig. 13.

A detailed process flow was utilized as in Fig. 14 to evaluate the finalized scores of the posture. The RULA score of *3* with low risks, changes may be needed was obtained for the designed chassis and posture positioning. The description of several scores according to the risk associated is tabulated in Table 3.

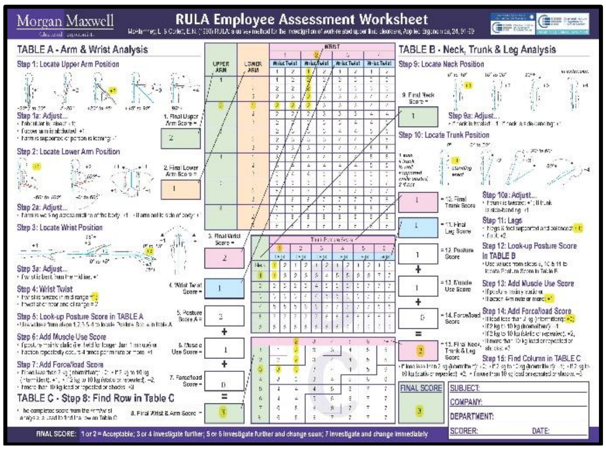

Fig. 13: RULA employee assessment worksheet.

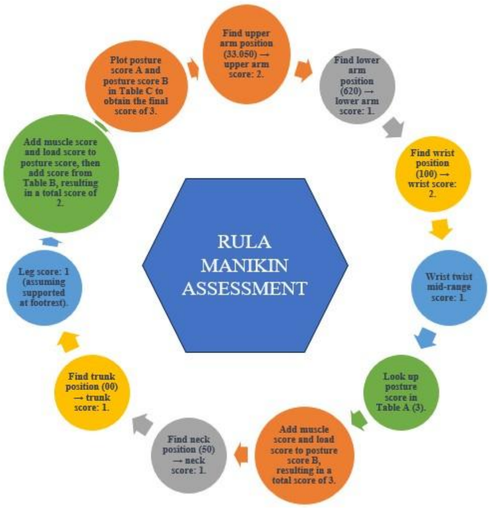

Fig. 14: RULA manikin assessment.

4.2 Rapid Entire Body Table (REBA)

The REBA method evaluates whole-body postural risks and musculoskeletal disorder (MSD) susceptibility by scoring key anatomical regions. A REBA score of 3 was obtained, indicating a low-risk level, though minor ergonomic adjustments may be warranted, as summarized in Table 4. The detailed procedure implemented in the REBA evaluation is depicted in Fig. 16. To assess the performance and the risk associated with the postural context of the entire body REBA assessment worksheet was used in which the scores with related postural constraints were then extracted and the overall postural score was evaluated Fig. 15.

Thus, A comprehensive human posture analysis was performed using CATIA's Ergonomic Design and Analysis tool, wherein a MANIKIN model, representing the driver's anthropometric dimensions, was positioned according to the settled posture Fig. 17. All relevant kinematic parameters and joint angles were meticulously measured, and the ergonomic evaluation was conducted under static, intermediate, and repetitive task conditions. The resulting data provides valuable insights into optimizing operator posture for reduced physical strain and improved task performance.

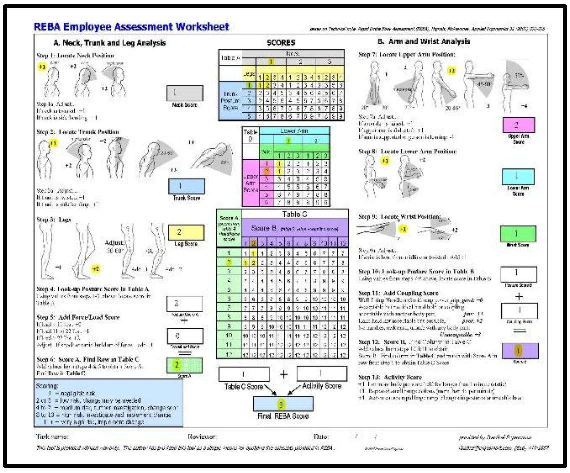

Fig. 15: REBA employee assessment worksheet.

Fig. 16: REBA mankin assessment.

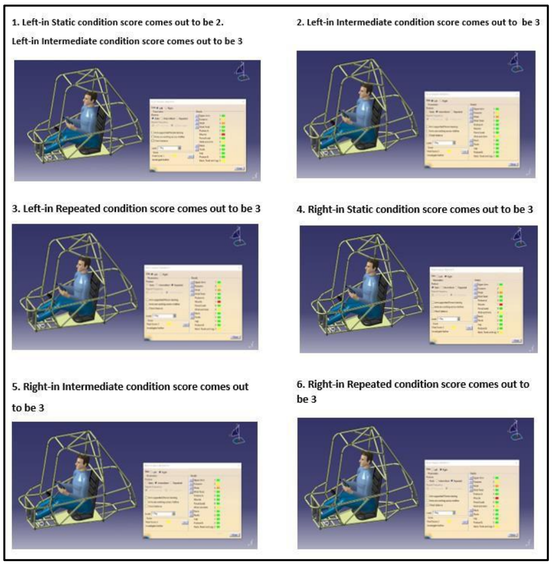

Fig. 17: Various views of ergonomic considerations by manikin.

Table 4. REBA action level table.

Score	Level of MSD Risks	Actions
1	Negligible	No change necessary
2-3	Low risk	May be change
4-7	Medium risk	Investigate, Change further
8-10	High risk	Change soon
10-15	Very High risk	Implement Change

5. Conclusion

This research work presents a comprehensive study on retrofitting a conventional IC engine-powered ATV into a HEV configuration as shown in Fig 18, providing a structured approach for addressing various influencing parameters. An ergonomically optimized design was developed using advanced ergonomic assessment tools. The key conclusions derived from this study are as follows:

- Weighted point approach significantly contributed to material selection, optimizing properties like Density, Modulus of Elasticity, Yield Strength, Ultimate Strength, and Cost, with assigned weights of 0.6, 1, 1.6, 2.1, and 0.1, respectively, on a 2.5 scale.
- Impact analysis resulted in an overall Factor of Safety (FOS) of 2.86, ensuring structural reliability under various impact conditions.
- RULA score of 3-4 and REBA score of 2-3 indicate low musculoskeletal disorder risk, with scope for design improvements.
- Developed chassis with retrofitting adaptability and integrated suspension systems for optimal performance on diverse terrains.
- Utilized parametric software for iterative refinements, ensuring an optimized and ergonomic ATV design.

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Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Fig. 18: Retrofitted hybrid electric vehicle.

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