Bio-mimicry of a Leopard Tortoise’ Shoulder Girdle in Space Frame Design of an Ambulance Body

Sarah A. Matiko

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BIO-MIMICRY OF A LEOPARD TORTOISE’ SHOULDER GIRDLE IN SPACE
FRAME DESIGN OF AN AMBULANCE BODY

by

Sarah A. Matiko

A Thesis Submitted to the College of Engineering Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
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BIO-MIMICRY OF A LEOPARD TORTOISE’ SHOULDER GIRDLE IN SPACE FRAME DESIGN OF AN AMBULANCE BODY

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This thesis was prepared under the direction of the candidate’s Thesis Committee Chair, Dr. Heidi M. Steinhauer, Professor, Daytona Beach Campus, and Thesis Committee Members Dr. Patrick N. Currier, Professor, Daytona Beach Campus, and Lisa K. Davids, Professor, Daytona Beach Campus, and has been approved by the Thesis Committee. It was submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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Abstract

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It appears that there is a need for affordable, functional and safe emergency medical support service vehicles in rural Sub-Saharan Africa (SSA). It is inferred that the road conditions have an influence on the availability, durability and affordability of motorized and non-motorized vehicles in rural areas. Also, it is deduced that locally modified bicycle and motorcycle ambulances are not conducive to maternal patients during emergencies. This study investigates the feasibility of modelling an ergonomically and crashworthy patient compartment for road conditions in rural SSA. The patient compartment is modelled by establishing geometrical requirements via a design standard for emergency medical support services and also, by using bio-mimicry as a design optimization technique. The bio-mimicry technique is conducted by extracting the skeletal architecture of a Leopard Tortoise’ shoulder girdles and transforming them into geometrical configurations of the patient compartment’s beam-columns. The geometrical features are then integrated with the design specifications of the selected baseline vehicle, Polaris Ranger 6×6 as well as the physical requirements of the patient compartment from an ASTM document (American Society of Testing Materials). A separate model with boxy configuration is created so as to evaluate the bio-mimicry design technique. Both configurations are assigned similar
material and physical properties which are deduced from low income resources and then, they are analyzed for crashworthiness through structural performances using computer-aided engineering software. The structural failures of both models are simulated using Ambulance Manufacturer’s Division’s static test requirements as well as Federal Motor Vehicle Safety Standards’ impact test specifications. It is concluded that bio-mimicked configuration of a shoulder girdle into structural beam-columns of a patient compartment provides a bottom heavy arrangement (more mass and volume), acts as a stress dissipater under static loading and energy absorbing elements during impacts particularly in the surrounding regions of the occupant.
Table of Contents

Thesis Review Committee: ................................................................. i
Acknowledgements ........................................................................... ii
Abstract ............................................................................................ iii
List of Tables ................................................................................... vii
List of Figures ................................................................................... viii
Introduction ....................................................................................... 1
  Significance of the Study ............................................................... 1
  Statement of the Problem ............................................................. 1
  Purpose Statement ........................................................................ 5
  Delimitations ................................................................................ 5
  Limitations ..................................................................................... 7
  Assumptions ................................................................................. 7
  List of Acronyms .......................................................................... 8
Review of the Relevant Literature ..................................................... 9
  Occupant Safety in Ground Ambulances, US .................................. 9
  Space Frame Bodies on All-Terrain Vehicles and Utility Vehicles .. 12
  Bio-Mimicry Strategy ................................................................... 14
  Research Question ....................................................................... 17
Methodology ..................................................................................... 18
  Bio-Mimicry Design Strategy ....................................................... 18
  Design Requirements and Constraints - Patient Compartment .... 22
  Designing and Analyzing Models of the Patient Compartments .. 28
Results ............................................................................................... 36
  Quantitative Data - Box Models and Bio-Mimicked Models ......... 36
  Descriptive Data on Body Loads and Impact Loads .................... 50
  Qualitative Data .......................................................................... 52
Discussion, Conclusions, and Recommendations ............................. 53
  Discussion .................................................................................... 53
  Conclusions ................................................................................ 56
  Recommendations ....................................................................... 57
Appendix A - Bibliography ............................................................... 58
Appendix B - Permission to Conduct Research ................................... 62
Appendix C - Data Collection Device ................................................................. 63
  C1 Computations in MATLAB ....................................................................... 64
Appendix D - Tables .......................................................................................... 91
  D1 Requirements Traceability Matrix (RTM) [CORE, SDD] ......................... 91
Appendix E - Figures ......................................................................................... 98
  E1 1400 lbf body load, additional and adjusted columns, 0.792” and 0.875” radii. 98
List of Tables

Table 1. Deduced physical requirements of the ambulance body ........................................23

Table 2. Deduced structural requirements of the ambulance body ........................................23

Table 3. Geometrical dimensions and payload capacities of Polaris’ Full-Size vehicles/Rangers ......................................................................................................................... 26

Table 4. Geometrical dimensions of the Tortoise’ trunk, ambulance, Polaris, and the bio-mimicked model .......................................................................................................................... 29

Table 5. The physical properties of bio-mimicked and box frame models ........................................ 37

Table 6. A summary of the minimum and maximum values of bio-mimicked and box models under earth’s gravity in x, y and z directions .............................................................................. 50

Table 7. A summary of the minimum and maximum values of bio-mimicked and box models under 1400 lbf in x, y and z directions. ............................................................................................ 51

Table 8. Static structural values of adjusted columns, 0.792 and 0.875 inches radii under 1400 lbf, x .............................................................................................................................................. 52

Table 9. Requirements traceability matrix .......................................................................................... 92
List of Figures

Figure 1. Maternal bicycle ambulances A and B ......................................................... 3
Figure 2. Maternal motorcycle ambulances C and D ...................................................... 4
Figure 3. Diagrams of upper and lower shells and shoulder girdles of turtles ............. 15
Figure 4. Skeletal 3D models of a Leopard Tortoise .................................................. 20
Figure 5. NURBS curves and ‘control points’ along the shoulder girdle ...................... 20
Figure 6. Fitted vs original curves of scapular prong and acromial process ............... 21
Figure 7. Images of transformed beam-columns and the girdles ............................... 22
Figure 8. Functional design elements of the patient compartment ............................ 23
Figure 9. Rescue vehicles built on Polaris Rangers, 6×6 800 and 700 Crew ............... 25
Figure 10. Overall dimensions of Polaris Ranger 6×6 (height and lengths) ............ 26
Figure 11. Chassis configuration of Polaris’ Ranger 6×6 ........................................... 27
Figure 12. Bio-mimicked and box frame under gravitational loads, z ..................... 31
Figure 13. Bio-mimicked and box frames with added columns under body loads, z .... 32
Figure 14. Bio-mimicked and box frames with adjusted columns under body loads, z .. 33
Figure 15. Rear impact settings for bio-mimicked frame and box frame ............... 34
Figure 16. Side impact settings for bio-mimicked frame and box frame .................... 34
Figure 17. Physical model of the bio-mimicked frame, front and right side views ....... 36
Figure 18. Physical model of the box frame, front and right side views ..................... 37
Figure 19. The floor chassis of Polaris Ranger along with the bio-mimicked frame ..... 37
Figure 20. Total deformations on bio-mimicked and box frames - earth load, x ........ 38
Figure 21. Total deformations on bio-mimicked and box frames - earth load, y ........ 39
Figure 22. Total deformations on bio-mimicked and box frames - earth load, z ........ 39
Figure 23. Max. combined stresses of bio-mimicked and box frames - gravity load, x .. 40
Figure 24. Max. combined stresses of bio-mimicked and box frames - gravity load, y .. 40
Figure 25. Max. combined stresses of bio-mimicked and box frames - gravity load, z .. 41
Figure 26. Total deformations on bio-mimicked and box frames - added columns ....... 42
Figure 27. Max. combined stress on bio-mimicked and box frames - added columns..... 42
Figure 28. Total deformation on bio-mimicked and box frames - 1400 lbf body load, x 43
Figure 29. Total deformation on bio-mimicked and box frames - 1400 lbf in y ............ 43
Figure 30. Total deformation on bio-mimicked and box frames - 1400 lbf in z ............ 44
Figure 31. Max. combined stress on bio-mimicked and box frames - 1400 lbf in x ....... 45
Figure 32. Max. combined stress on bio-mimicked and box frames - 1400 lbf in y ........ 45
Figure 33. Max. combined stress on bio-mimicked and box frames - 1400 lbf in z ....... 45
Figure 34. Total deformations on bio-mimicked and box frames - rear impact ............ 46
Figure 35. Total deformations on bio-mimicked and box frames - side impact I view.... 47
Figure 36. Total deformations on bio-mimicked and box frames - side impact F view... 47
Figure 37. Total deformations on bio-mimicked and box frames - rear added columns.. 48
Figure 38. Total deformations on bio-mimicked and box frames - side added columns. 48
Figure 39. Total deformations on bio-mimicked and box frames - rear final frame ....... 49
Figure 40. Total deformations on bio-mimicked and box frames - side final frame ....... 50
Figure 41. Min. combined stress vs acceleration loads of the bio-mimicry frame, y ...... 51
Figure 42. Min. combined stress vs acceleration loads of the box frame, y .................. 51
Figure 43. Deformation on adjusted bio-mimicked frame (0.792 and 0.875) ............... 98
Figure 44. Direct stress on adjusted bio-mimicked frame (0.792 and 0.875) ............... 98
Figure 45. Max. combined stress on adjusted bio-mimicked frame (0.792 and 0.875)... 99
Figure 46. Min. combined stress on adjusted bio-mimicked frame (0.792 and 0.875) .... 99
INTRODUCTION

Significance of the Study

The findings from this research could provide insights on the safety of emergency medical vehicles in rural Sub-Saharan Africa (SSA). Additionally, this study could contribute to body designs of all-terrain vehicles. In particular, the space frame designs of ambulance bodies that are mounted on utility vehicles. First, it is deduced that the transportation methods that are used during maternal emergencies reflect the transportation challenges that are faced in rural settlements. It is assumed that the challenges could be addressed by understanding the types of vehicles in rural SSA as well as the impacts of geographical conditions on the vehicles during medical emergencies. Second, it is implied that by adopting the design and manufacturing standards of ambulance bodies as practiced in the United States, a crashworthy design model may be obtained compared to the existing ambulance vehicles in rural SSA. Third, it is deduced that by configuring the support structures of the ambulance body to the shoulder girdles of a Leopard Tortoise, a bio-mimicry strategy in body design of all-terrain vehicles may be employed as a design optimization technique. Bio-mimicry involves investigating and implementing biological solutions from forms of nature, or processes or the ecosystems [58].

Statement of the Problem

It appears that there is a lack of affordable, functional, and safe medical vehicles in rural Sub-Saharan Africa during obstetric emergencies. Obstetric emergencies involve the care of a mother and a baby or fetus during preterm labor, postpartum hemorrhage,
preeclampsia, eclampsia (frequent seizures), amniotic fluid embolism, uterine inversion and abdominal pregnancy [59].

**Emergency Medical vehicles and Road Conditions in rural SSA.** Studies indicate that the lack of appropriate medical vehicles in low-income settlements are attributed to the types of the vehicles as well as the conditions of the roads. As a result, rural dwellers incur transportation delays and sometimes discomfort as they tend to use bicycle and motorcycle ambulances during emergencies. Also, it is observed that a large number of road vehicles in SSA are usually imported second-hand vehicles that are not designed for unpaved road conditions [39]. And, during obstetric emergencies, it has been reported that delays in reaching and receiving immediate care contribute to maternal mortalities, fetal death, and sometimes maternal complications in both low- and middle-income countries [13]. It is likely that the delays in reaching the health facilities are due to limited infrastructure as it is estimated that more than 60% of people in low income countries live more than eight kilometers from a health facility [25]. Additionally, it is reported that irregularity of road maintenance has contributed to deterioration of 50% of paved roads and 80% of unpaved roads in SSA hence, the unfavorable road conditions compounded with the body position (sitting position) as well as the body movements during maneuvers are likely to cause discomfort during emergency transportations [25]. Combined with geographical conditions such as topography (hilly), climate (heavy rains) and soil structure (clay), it appears that proximity to the health facilities as well as the road
conditions significantly impact the duration of travel while seeking immediate health care in rural SSA [20] [40].

In an effort to improve access to health care, local communities and international organizations continue to support initiatives on bicycle and motorcycle ambulances in low-income countries [62] [63]. For instance, through the Transaid project, it is reported that within six months of implementation, 86% of the trips that were made from three rural districts: Petauke, Chipata and Katete in Zambia to the health centers via bicycle ambulances were life-saving [55]. And, in Makanjira Malawi, through the Safe Motherhood Project in collaboration with Riders for Health, it is reported that obstetric patients who travelled via motorcycle ambulances arrived 35% faster to the health centers compared to those who travelled via the ambulance vehicle [53]. While local modes of transportation offer affordable options to rural dwellers, it appears that the operability of bicycle and motorcycle ambulances are limited by unfavorable geographical and road conditions as well as the capabilities and safety of the vehicles [25]. For example, bicycle ambulances require wide turns while motorcycle ambulances are prone to toppling. Figure 1 shows two attachment configurations of patient compartments to bicycles ambulances. A is attached near the rear cog and B is secured on the seat post [60] [61].

Figure 1. Maternal bicycle ambulances A and B [60] [61]
Figure 2 shows two different set-ups in which patient compartments are mounted on motorcycles. Motorcycle ambulance C is built by eRanger where a sidecar is attached to the motorcycle while the patient compartment in motorcycle ambulance D is attached to the rear [64] [56].

From Figures 1 and 2, it appears that the patient compartments aren’t configured to standard requirements that pertain to geometry, materials or medical devices and equipment. As such, the patient compartments rarely provide sufficient room for obstetric patients to be transported in the recommended position: left lateral decubitus position [59]. Also, it is likely that geometrical and towing constraints of the vehicles limit accommodation of an additional person that could offer urgent medical services during transit. Moreover there are safety concerns on the use of motorcycle ambulances under unfavorable weather conditions. A study on motorcycle crashes (Egypt) indicates that motorcyclists and their passengers are 53% more likely to be in a collision when it is rainy, cloudy and windy [15]. And in Kenya, a study on motorcycle injuries (Kenya) shows that only 43 of motorcyclists and passengers wear helmets [9]. Thus, it appears that costs, safety and the functionalities of the patient compartments that are mounted on bicycles and
motorcycles are structurally, dynamically and medically limited by the types of the vehicles in rural SSA.

**Purpose Statement**

The objective of this study is to investigate the feasibility of developing a sustainable ambulance vehicle for obstetric emergencies in rural SSA. The focus will be on selection of a viable baseline vehicle and, integration of an ergonomic and crashworthy patient compartment onto the vehicle. The vehicle shall be selected by considering the cost, structural layout, and vehicle performance of all-terrain vehicles in SSA via internet search engines. On the other hand, an ergonomic and crashworthy patient compartment shall be determined through specified requirements for emergency medical support services. And, using bio-mimicry as a design optimization technique, the acquired physical requirements shall be embedded within the physical constraints of the baseline vehicle. The design requirements shall be obtained from the Standard Practice for Design, Construction, and Procurement of Emergency Medical Services Systems (EMSS) Ambulances while the design constraints shall be deduced from the vehicle’s manufacturing manual. Lastly, the structural failure (deformation) of the patient compartment shall be evaluated using the ambulance body test requirements that are specified by the Ambulance Manufactures Division as well as the Federal Motor Vehicle Safety Standards (FMVSS).

**Delimitations**

This research is delimited by the selected topic, the articles that were used to develop the investigation as well as the software that were used to model and analyze the patient compartment. Even though transportation delays are attributed to maternal
mortalities in middle- and low-income countries, this study focused on transportation challenges in rural SSA. As such, through the library search engine, peer reviewed and non-reviewed articles were used to understand the scope of the transportation challenges during obstetric emergencies. Similarly, the library search engine was used to obtain research materials on ambulance bodies, all-terrain vehicles, bio-mimicry as well as terrestrial turtles.

Even though the ambulance vehicle is intended for regions in SSA, American standard documents: ASTM F2020-02a, FMVSS and AMD are used in this investigation as part of the course curriculum. The ASTM document was used to extract physical and structural requirements of the patient’s compartment while the FMVSS and AMD documents were used as guiding materials in evaluating the structural performances of the designed models. Unlike the standard documents, articles on all-terrain vehicles in Kenya, Europe, Canada, and the United States were used to investigate the functionalities as well as the safety of utility vehicles which are usually built as space frame bodies. With the effort of “copying” the skeletal configuration of terrestrial turtles into the patient configuration of the ambulance body, peer reviewed articles were used to investigate the morphological and behavioral characteristics of terrestrial turtles.

Finally, computer-aided designs and computer software namely, 3D Slicer, 3D, Rhino, MATLAB and ANSYS were used to reverse engineer the skeletal model of a turtle, to represent the skeletal geometry into a chassis configuration and lastly, to study the deformations of the models under various loads. The availability of 3D Slicer as an open source software and Rhino as a 90 day free trial enabled reverse modelling of medical images of a Leopard Tortoise to representations of the shoulder girdles as data points (x,
y, and z). Both MATLAB and ANSYS were accessible through the university computers. Additionally, MATLAB enabled data entry and manipulations as local co-ordinates while ANSYS enabled geometrical modelling as well as static and dynamic analysis.

**Limitations**

There are limitations to this investigation that are associated with the researcher as well as the materials and the tools that are used in conducting the research project. There are potential bias to the study area and the selection of the baseline vehicle in that, the researcher is a native of Africa and is familiar with the vehicle manufacturer through collegiate competitions, Baja S.A.E (Society of Automotive Engineers). Thus the materials used to define the objective of the study may be subjective. Quantitatively, limited access to data, lack of specifications on ambulance dynamic crashworthiness and computational approximations influenced the duration, the types of analysis and the actual values obtained from the research project. For instance, only one set of datum is used to define the bio-mimicked structural elements so the design configuration may not be robust. Also, while efforts are made in this study to incorporate structural safety requirements, it appears that ambulance vehicles are evaluated on static performance via AMD and are not required to meet dynamic requirements as specified by the FMVSS and also recommended by the National Highway Traffic Safety Association (NHTSA) [14] [11] [12].

**Assumptions**

While fitting the data values of the shoulder girdles using best least-squares plane method, the images of one Leopard Tortoise were assumed to be sufficient for mimicking the structural elements. In this study, it is also assumed that the static load tests that are
defined by the AMD are adequate for illustrating crashworthiness of modeled patient compartments. Lastly, it is assumed that the computed designs and values are approximate representations of the actual models such that in the event of testing the model, the baseline vehicle shall be available along with the selected materials.

List of Acronyms

4WD  Four-Wheel Drive
AMD  Ambulance Manufacturer’s Division
ASTM  American Society of Testing and Materials
ATV  All-terrain vehicle
CT  Computed tomography scans
DICOM  Digital imaging and communications in medicine
EMSS  Emergency Medical Services Systems (EMSS) Ambulances
F2020-02a  Standard Practice for Design, Construction, and Procurement of (EMSS)
FMVSS  Federal Motor Vehicle Safety Standards
M-ATV  Military all-terrain vehicle
NHRA  National Hot Rod Association
NHTSA  National Highway Traffic Safety Administration
NURBS  Non-Uniform Rational B-Spline
SAE  Society of Automotive Engineers
SSA  Sub-Saharan Africa
STL  Standard Tessellation Language
REVIEW OF THE RELEVANT LITERATURE

To design an ambulance body that is safe and functional for rural SSA, research materials on safety criteria for ground ambulances as well as the failure mechanisms of space frame bodies on utility vehicles were investigated via the library database. Additionally, to optimize geometrical configuration of the ambulance body via bio-mimicry strategy, the skeletal properties of terrestrial turtles were studied using the library’s database and also, the encyclopedia on Testudinidae.

**Occupant Safety in Ground Ambulances, US**

In the United States, container or ‘box like’ ambulance bodies are usually mounted on a conventional truck chassis or a cutaway van chassis and are referred to as Type I and Type III ambulances in the ASTM F2020-02a document. However, in rural Sub-Saharan Africa, Figures 1 and 2 show that “trailer” like patient compartments are usually attached to bicycles, motorcycles and sometimes ox-carts which are operated as low-cost options for ambulance vehicles. To maintain the safety of the occupants, a Haddon Matrix dictates that the conditions of the humans, the safety of vehicles, and the environmental conditions must be met in three periods: pre-crash, crash, and post-crash [23]. From the Haddon Matrix, it appears that the bicycle and motorcycle ambulances do not meet at least three of the required conditions as occupants tend to sit or lie in non-supine position. Also some of the low-cost ambulances have open patient compartments as such, when not properly restrained, the occupants are likely to be ejected during or after a crash. While this study will not be investigating the impacts of restraints on occupant safety, a report by the NIOSH Fire Fighter Fatality Investigation shows that a side impact of an ambulance vehicle to a tree resulted into the death of a restrained patient as well as the ejection of a non-restrained
paramedic [27]. It is also reported that at the time of crash, the weather was rainy and cloudy, and, the vehicle had worn out tires in addition to structural deformations on the roof as well as on the street side of the patient compartment [27]. Thus, even with closed patient compartments that are developed and tested in Unites States, there exist a need to prevent or reduce injuries and fatalities by making improvements on existing configurations/models. Currently, the Federal Motor Vehicle Safety Standards (FMVSS) are organized into series of 100, 200, 300, and 500 requirements where the former is associated with accident prevention followed by injury protection, then post-accident protection and the latter is attributed to other regulations like vehicles with low speed [24]. In this investigation, the focus shall be on designing an ambulance body that aims to protect the occupant from injuries pre-crash and during crash within rural SSA’s road conditions as well as weather conditions.

**Crashworthiness of patient compartments, US.** For occupant safety, the crashworthiness of vehicles are evaluated via FMVSS. Crashworthiness refers to the structural integrity of the vehicle’s body under static or dynamic loading in reference to the survival space of the occupant [29]. While the design, construction, and procurement of ambulance vehicles (ASTM F2020-02a) require the satisfaction of FMVSS standards for EMSS certification, it appears that the FMVSS safety standards on occupant crash protection (208), side impact protection (214) among others are not enforced on ambulance bodies instead, the structural performance of ambulance bodies are subject only to AMD Standard 001 (Static Load Test) [12] [24] [11]. Thus, it is likely that the structural integrity of ambulance bodies that are not built by the original equipment manufacturer may be limited more so, the rear patient compartments. There are reports that attribute non-
crashworthiness of Type I and Type III ambulance vehicles to construction as well as the attachment points of the rear patient compartments to the conventional cab-chassis in Type I and cutaway can cab-chassis in Type III ambulance vehicles [28] [11]. And, an investigation on the side impacts of a moving Type II ambulance onto a stationery Type I ambulance vehicle as well as a moving Type II ambulance onto a stationery Type III ambulance reports that upon impact, both Type I and Type III ambulances rolled onto their sides revealing the need validate the structural performance of ambulance vehicles under dynamic loads [30]. Additionally, it appears that the static load requirements that are defined by the FMVSS for passenger safety differ from those defined by the AMD for occupant safety (patient compartment box). For instance, during roof crush test, in FMVSS No. 216 the simulated load (plate) is applied at a 5-degree angle longitudinally and 25-degree laterally while in AMD S6.1, a rectangular force is applied vertically downwards [24] [12].

Hence, it is deduced from the documents and the reports that the exclusion of structural safety measures in the design, assembly or the validation of the ambulance bodies by either the regulatory bodies or the ambulance manufacturing bodies in the US minimizes the safety of the occupants during and after crash conditions more so on Type I and Type III ambulance vehicles. While it is understood that the safety standards in the US are more advanced than those in SSA, it appears that there exist a need for design and manufacturing improvements of the current patient compartments in the US. The intent of this investigation is to adopt the highest US safety practices into the design method. Since this study involves designing an ambulance body for rural SSA, it is deduced that the economic
resources within SSA will influence the availability of the baseline vehicle, parts, and even fabrication methods of the designed patient compartment.

**Space Frame Bodies on All-Terrain Vehicles and Utility Vehicles**

In comparison to unit bodies, space frame bodies tend to be lighter in weight, easier to assemble and sometimes, cheaper to develop. For instance, by reconfiguring a standard ‘container like’ body with space frame parts, 3CR12 (steel chrome) a vehicle body builder Coachwork maintained the structural integrity of the ambulance body while reducing weight and also providing additional space which enabled accommodation of patients with special needs i.e. with wheel chairs [16] [22]. And, for assemble ability and transportation, space frame elements were used in the UK to design and build a light truck vehicle, OX for road conditions in Africa and other developing countries that is, capable of carrying up to 15 people or cargo weighing about 4400 lbs. [31]. In Kenya, Mobius Motors designs and fabricates the structural frames of sports utility vehicles using high strength steel tubes [7]. Additionally, studies on off-road vehicles indicate that all-terrain vehicles are also used for recreational activities in other parts of Africa like South Africa particularly along the coastal beaches [32] [33]. When configured with suitable materials and fabrication processes, it is likely that space frame elements could be utilized in designing suitable, functional, maintainable, and cost effective space frame bodies for occupants and for this study, maternal patients in rural SSA.

**Crashworthiness of space frame utility vehicles**

Articles and reports from developed countries like the US and Canada were used in this study to evaluate the safety of space frame bodies. This is because the literature (reviewed) was accessible via the library database. Investigations on injuries and fatalities
mostly associated utility vehicle accidents with the drivers’ lack of following safety protocol like wearing helmets, and using seat belts. For instance, a study on mortality rate of all-terrain vehicles across 50 states observed that the states with the highest mortality rate, West Virginia and Alaska are mostly inhabited by less educated rural dwellers who rarely observe safety measures [36]. And, an investigation on the types of crashes and body impacts (head, abdomen or thorax compression, blunt force) of ATV fatalities in West Virginia indicates that in both circumstances: crashes on the highway; collisions 55.6%, rollovers 11.1%, and ejections 22.2 and off-road crashes; collisions 12.1%, rollovers 55.2%, and ejections 17.2% that the body frame failed in protecting the occupants even though, more than half of the decedents tested positive for alcohol or drugs and that majority of the operators, 84.6% didn’t wear helmets [41].

Besides fatalities as well as injuries, studies on the safety of utility vehicles show that there is trend of space frame structures being non-crashworthy and the vehicles being unstable particularly on uneven surfaces. In one article, the crashworthiness of the space frame body of a utility vehicle is investigated by simulating a frontal pole impact, a side pole impact, a barrier rear impact and a rollover impact in accordance with the FMVSS standards via ANSYS, the results indicate that frame significantly deforms, twists and even fractures during rollover [38]. Also, studies on dynamic stability of all-terrain vehicles associate rollover risks to low static stability due to a combination smaller track width and higher center of gravity (high ground clearance) compared to standard passenger vehicles and, since utility vehicles tend to have low curb weight when occupied/loaded, the stability factor usually decreases making it easier to tip or rollover more so, during lateral maneuvers like making turns [46] [47].
While it may be feasible to develop a cost-effective space frame body for off-road conditions in SSA, it appears that these structures fail under dynamic loads hence the need to improve the safety of all-terrain vehicles as well as utility vehicles. To improve occupant protection, this study aims at optimizing the design configuration of a patient compartment with space frame elements via bio-mimicry.

**Bio-Mimicry Strategy**

While the intent of this investigation is to design a patient compartment structure that is crashworthy and affordable in low-income settings, literature on crashworthy and utility vehicles show that unlike space frame structures, standard unit bodies are designed to absorb crash energy and, are required to have minimal intrusion into the space of the occupant per FMVSS. Additionally, standard off-road vehicles have better operation and handling capabilities compared to light all-terrain vehicles or utility vehicles. In this study, it is assumed that occupant safety of patient compartments could be improved by manipulating the architecture of the structural elements through bio-mimicry. Mercedes-Benz for instance developed a bionic body frame by ‘copying’ the shape of a boxfish which enabled increase in strength to weight ratio and decrease in drag thereby reducing fuel consumption [4]. Design for crashworthiness usually involves multi-disciplinary processes, biological solutions are usually synthesized by nature from various elements. As such, morphological features and behaviors of terrestrial turtles were considered to represent structural arrangements and dynamic (impacts) performances of all-terrain vehicles respectively. Morphology refers to the form and structure of an organism as well as the associations among the structures of an organism while behavior is defined as the sum of the responses of an organism to internal or external stimuli [49].
Geometrical properties of terrestrial turtles. Geometric morphometric properties of turtles are investigated so as to map the structural advantages of a terrestrial shell to mechanical advantage of a patient compartment. Terrestrial or land turtles belong to the family of Testudinidae: their skeletal structure consists of a carapace or upper shell which is layered with interconnected bones, ribs, and vertebrae that are fused by a bony bridge to the plastron (lower shell) [48]. Morphometric studies indicate that carapaces and plastrons have structural locomotive features such that, the flatness and broadness of aquatic carapaces enhances hydrodynamic movements while the size and shape variations of terrestrial carapaces and plastrons i.e. highly domed to flat and thin enables the land turtles to maneuver land terrains [42] [48]. In another study, it is observed that geometrical features of carapaces and plastrons correspond to the sizes, shapes and orientations of turtle’s shoulder girdles in terrestrial, fresh water, and marine environments [43]. Figure 3 shows schematic diagrams of shoulder girdles as enclosed within the upper shells, curved double lines as well as lower shells, indicated by straight outlines of terrestrial, fresh water and marine turtles [43].

![Figure 3. Diagrams of upper and lower shells and shoulder girdles of turtles [43]](image)

Therefore, it is deduced that the skeletal configurations of terrestrial turtles are specialized to function within the natural habitats particularly the carapaces and plastrons. It is also understood that the dimensions of the support elements like the shoulder girdles also adjust within the size and shape of the carapaces as well as the plastrons. By implying
that shoulder girdles act like the main beams which support the weight of the trunk, then identifying a terrestrial turtle within SSA terrain could aid in investigating a geometrical advantage of mimicking the skeletal dimensions and translating them to the structural configurations of the patient compartment.

In addition to structural support functions, a geometrical study illustrates that the shapes of carapaces and plastrons or upper and lower shells of terrestrial turtles assist with dynamic stability. The study shows how righting strategies of flat, medium and tall turtles highly correlate with the height/width ratio of the upper and lower shells; such that, turtles with values close to 0.9 (where 1 is the ideal ‘righting’ value) like Leopard Tortoises gain stability with minimal neck movements and limb efforts while flat turtles, less than 0.6 like side neck turtles primarily overcome instability by their necks [44]. In the same study, it is observed that while the curvature of the carapaces in high domed turtles as well as the neck maneuverability of flat turtles assist with the ‘rolling’ behavior of high domed turtles, the location of center of gravity plays a significant role in shifting the weight to stability [44]. The study reports that the center of gravity of high domed turtles is closer to the plastron than the center of its main cross-section enabling the turtles to self-right [44].

Therefore, in addition to geometrical advantages of the shoulder girdles (size, shape, and orientation) and the shells (height/width), it appears that the ‘bottom heaviness’ of the turtle enhances the righting capabilities of high domed terrestrial turtles. Even though this research will not be focusing on the dynamic performance of the vehicle, geometrical contributions of the shape as well as the height/weight ratio of carapaces to the righting strategy will be incorporated by mimicking a high domed turtle’ shell like that of a Leopard Tortoise’ and then configuring the size and shape of a patient compartment.
Summary

Through reviewed literature on occupant safety, space frame bodies on utility vehicle, and bio-mimicry as a design approach, it is deduced that developing a safer and low-cost ambulance vehicle than a bicycle or motorcycle ambulance is feasible. It is implied that the crashworthy reports (US) are recommending structural improvements of current patient compartments particularly Type I and Type III ambulance vehicles. It is also understood that while space frame structures provide weight and cost reductions, they limit the crashworthiness of the vehicle upon impact. Additionally, studies show that due to narrower track width and higher ground clearances, utility vehicles are less stable than standard passenger vehicles. With the intent to reduce structural deformations through geometrical configuration, the review on geometrical features of turtles illustrate that the skeletal configurations of the carapaces, plastrons and shoulder girdles are specialized in size, shape, and orientation to the natural habitat of the specie.

Research Question

Do the geometry configurations of bio-mimicked frames provide lower structural deformations on the beam-columns and, lower stress concentrations at the mounting joints than the box like or container like geometry arrangements?
METHODOLOGY

The mechanical advantage of the size, shape, and orientation of a Leopard Tortoise shoulder girdle as an optimized configuration for the beam-column geometry of a vehicular body is investigated by capturing and transforming the allometry (size-shape changes) into the physical dimensions of a patient compartment and then observing the failure behaviors through structural analysis. Using computer aided tools, namely Slicer 3D, Rhino, CORE, FEMAP and ANSYS the architecture of the shoulder girdles are mimicked into the support structures of the patient compartment. The requirements on design, construction and tests of the rear patient compartment are compiled in tabular forms and the structural characteristics and materials of the baseline model are embedded with the acquired dimensions as well as the selected materials as finite element models. Even though vehicle response and occupant response (restraint systems, dummy) to various crash tests dictate the overall safety of the occupant, the kinematics of the occupants are not studied in this project. However, the structural performances of the designed models (bio-mimicked frame) and the comparison model (box frame) are evaluated within the yield strength of the selected material by monitoring the stresses, the deformations and the intrusions of the structural members into the space of the occupant through static and dynamic simulations.

Bio-Mimicry Design Strategy

In a bio-mimicry study, a prototype of a jumping and gliding robot was developed in two stages: by ‘copying’, the size and the shape of a locust’s wings, the flapping mechanism of the wings, the abdominal pitch and yaw mechanism; and by evaluating the structural deformations of the wings via finite element modelling and analysis [3]. While a prototype will not be developed in this investigation, a two part design process similar to
morphometric study of the jumping and gliding robot is employed by formulating geometrical properties of a Leopard Tortoise’ shoulder girdle into the support columns of a patient compartment and, by evaluating the structural performance of the mimicked frame via finite element modelling and analysis. The mimicry of the shoulder girdles is realized by extracting the dimensions from the 3D model of a Leopard Tortoise and translating those values to the physical dimensions of the patient compartment through parameterization. Static and impact analysis are performed via FEA on the mimicked patient compartment so as to evaluate the structural integrity of the model.

**Modelling the shoulder girdles.** It is assumed that the population density of Leopard Tortoises across Eastern and Southern Africa dictates survivability and longevity of the species within the SSA terrain [48]. As such digital data of a Leopard Tortoise were obtained as medical images in 2D (CT scans), then remodeled into a 3D image which enabled extraction of shoulder girdles that were parameterized into plane equations and formulated as geometrical configurations of the frame’s (patient compartment) beam-columns.

Medical images are acquired as Digital Imaging and Communications in Medicine (DICOM) files from CT scans which are then segmented into STL files via a visualization and image analysis software, 3D Slicer. The DICOM files, are loaded into the 3D Slicer software via the DCM icon to visualize the 2D anatomical images, then the images are cropped to obtain the region of interest followed by volume rendering, projecting and visualizing into a 3D model and lastly, saved in STL format, Standard Tessellation Language [19].
Using Rhino, a computer graphics and computer aided design software, the STL files, imported as triangulated meshes, are preprocessed by separating the meshes and checking for damages and then the shoulder girdles are remodeled as surface curves via a plugin software, Rhinoresurf [18]. Figure 4 shows the axial view of a meshed shell (S) separated from the sagittal view of the internal skeleton structure (T) and ‘cleaned’ meshed models of preprocessed shoulder girdles and pelvic girdles (PS).

![Figure 4. Skeletal 3D models of a Leopard Tortoise](image)

The shoulder girdles, specifically the right shoulder girdle is remodeled into NURB’s curves through the RhinoResurf plugin so as to mathematically represent the curvature of the girdles as data points, (x, y, and z) [54]. Figure 5 shows ‘control points’ along NURBS curves (black lines) of the right shoulder girdle also referred to as a triradiate structure as it consists of a scapular prong, acromial process and coracoid.

![Figure 5. NURBS curves and ‘control points’ along the shoulder girdle](image)

**Parameterizing the shoulder girdles.** Using the best least-squares plane method via MATLAB, the data points of the triradiate structures are parameterized into plane
equations by first formulating the piece-wise curves of the scapular prong and acromial process followed the coracoid [34]. The formulation is conducted by obtaining the centroid of the curve’s point mass and the corresponding normal vector that minimizes the sum of the weighted squared distances to the plane [B2]. Figure 6 shows fitted, (green) and original (blue) data points of the scapular prong and acromial process.

Figure 6. Fitted (green) vs original (blue) curves of the scapular prong and the acromial process [35]

**Translating the shoulder girdles to beam-columns.** The geometry of the shoulder girdles are configured to the geometry of the beam-columns by segmenting the data points that are closest to the plane (0.1%) into straight and curved sections so as to simulate straight and curved metal parts. Furthermore, the segmented geometry is positioned just as the girdles are placed on the plastron through reflections, y-z direction for right and left girdles as well as x-y direction for shoulder and pelvic girdles. Figure 7 shows the
segmented and reflected (x-y) geometry of the beam-columns (BC) next to the sagittal view of shoulder girdles and pelvic girdle (SG).

![Image](image1.png)

**Figure 7. Images of transformed beam-columns via FEMAP and the girdles via Rhino [17] [18]**

**Design Requirements and Constraints - Patient Compartment**

Design considerations of the patient compartment are made by identifying the design requirements as well as the design constraints. The requirements are obtained from the Standard Practice for Design, Construction, and Procurement of Emergency Medical Services Systems (EMSS) Ambulances while the design constraints are established from the specifications of the baseline vehicle and the material properties of the designed model. A systems engineering software, CORE is used to compile physical and structural requirements pertaining to the patient compartment. The CORE software functions as a model-based engineering system where a layered approach is used to develop a complex solution in an efficient and traceable manner throughout the design process [50]. And for design constraints, internet search engines are used to select an affordable vehicle with off-road capabilities and a suitable space frame material for low-income areas.

**Selecting design requirements from ASTM-F2020-02a.** The standard documents defines multiple design test requirements for ambulance vehicles. However, the focus of this study is to configure a mimicked patient compartment into a utility vehicle. As such the seven (6.1, 6.2, 6.3, 6.4, 6.5, 6.6, and 6.10) physical and structural requirements that
are associated with the ambulance body were used in this research. The sub-systems and components that didn’t have dimensional or structural relationships with the ambulance body were not considered in this investigation. The physical and structural requirements that were retrieved from the standard document are listed in Table 1 and Table 2 respectively.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Physical Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Ambulance</td>
<td>Type of mounting vehicle</td>
</tr>
<tr>
<td>Configuration, Basic Life Support</td>
<td>Patient accommodation</td>
</tr>
<tr>
<td>Vehicle Physical Dimensional Requirements (inches)</td>
<td>Length, width, height (246, 79-84, 110)</td>
</tr>
<tr>
<td>Cab to Axle</td>
<td>Outside body length, less than 50%</td>
</tr>
<tr>
<td>Cab/Patient Compartment Access Window (inches²)</td>
<td>Area, 150</td>
</tr>
<tr>
<td>Emergency Medical Technician Seating (inches)</td>
<td>Depth, width, height (18, 18, 15-18)</td>
</tr>
<tr>
<td>Patient Compartment Interior Dimensional Parameters (inches)</td>
<td>Length, width, height (122, 18 ± 6, 60)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Geometrical Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambulance Components, Equipment, &amp; Accessories</td>
<td>Standard items</td>
</tr>
<tr>
<td>Recovered Materials</td>
<td>New materials</td>
</tr>
<tr>
<td>Body General Construction</td>
<td>All welded aluminum, strength (top and sides)</td>
</tr>
<tr>
<td>Vehicle Performance</td>
<td>Chassis manufacturer data</td>
</tr>
<tr>
<td>Payload Allowance</td>
<td>2 patients, 1 driver, and 1 EMT @ 175 lbs.</td>
</tr>
<tr>
<td>Ambulance Body Structure</td>
<td>Secure, rust-resistant attachment</td>
</tr>
<tr>
<td>Body Mounting</td>
<td>Stability, minimize height</td>
</tr>
</tbody>
</table>

While retrieving the requirements, it was realized that the specifications of the patient compartment were interrelated with geometrical and structural performance of other components. Thus the retrieved requirements were analyzed by importing the requirements into CORE’s database as elements, establishing component based and
function based relationships, and generating the physical architecture of the elements (requirements) in traceable forms. Figure 8 shows a functional behavior model of an ambulance body, extracted as requirements and illustrated in CORE as elements.

Figure 8. Functional design elements of the patient compartment

**Selecting the baseline vehicle for the ambulance body.** The feasibility of a motorized all-terrain vehicle for rural SSA is determined through the market density of manufacturers as well as the distributors of ATV products across SSA. After the baseline vehicle is selected, electronic manuals (service and owner’s) and field trip observations are used to configure the frame of the patient compartment into an ambulance body [51]. Using the following terminologies: ATV Africa, all-terrain vehicle Africa, off-road vehicle
Africa, 4x4 Africa, and 4WD Africa, the vehicles (Jeep, Polaris, Honda, and John Deere) that are relatively inexpensive, present across Africa, and are also capable of hosting a patient compartment are filtered so as to select the vehicles that are affordable, maintainable (components are available for replacements) and modifiable into a sustainable off-road ambulance. In developed countries like the United States of America it is more common to see ambulance vehicles that are designed for the highway than off-road conditions. But, business articles indicate the existence of military ambulance vehicles (M-ATVs) and rescue vehicles as ATV ambulances like the one developed by the Alternative Support Apparatus (ASAP) with container like structure or Homebrewed UTV with space frame structures as shown in Figure 9 [45] [52].

Thus, in addition to Polaris’ Ranger 6x6 800 being modifiable to an off-road ambulance vehicle, the availability of a manufacturing outlet in South Africa and several distributors in East and North Africa illustrates the suitability of the vehicle. Additionally, other full-size vehicles that are manufactured by Polaris were reviewed by compiling technical specifications on payload and geometry (vehicle size, ground clearance and bed box dimension) as illustrated in Table 3.
Table 3. Geometrical dimensions and payload capacities of Polaris’ Full-Size vehicles/Rangers

<table>
<thead>
<tr>
<th>Polaris Ranger</th>
<th>Dry Weight, (lb.)</th>
<th>Vehicle Size (inches)</th>
<th>Ground Clearance (inches)</th>
<th>Bed Box (inches)</th>
<th>Payload (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew 570 EFI</td>
<td>1100</td>
<td>114×60×74</td>
<td>10.5</td>
<td>36.5×54×11.5</td>
<td>1500</td>
</tr>
<tr>
<td>Ranger XP 570</td>
<td>1320</td>
<td>116.5×60×76</td>
<td>12</td>
<td>36.5×54×11.5</td>
<td>1500</td>
</tr>
<tr>
<td>Ranger Diesel HST</td>
<td>1915</td>
<td>123.5×64×74</td>
<td>10</td>
<td>43.5×54×11.5</td>
<td>1750</td>
</tr>
<tr>
<td>Ranger 6×6 800</td>
<td>1551</td>
<td>137×60×76</td>
<td>12</td>
<td>42.5×54×11.5</td>
<td>2000</td>
</tr>
<tr>
<td>Ranger Diesel</td>
<td>1430</td>
<td>116.5×60×76</td>
<td>12</td>
<td>36.5×54×11.5</td>
<td>1500</td>
</tr>
<tr>
<td>Ranger XP 900</td>
<td>1318</td>
<td>116.5×60×76</td>
<td>12</td>
<td>36.5×54×11.5</td>
<td>1500</td>
</tr>
</tbody>
</table>

Amongst the vehicles listed in Table 3, Ranger 6×6 800 appears to be the most suitable vehicle as it has the most payload capacity and largest overall vehicle dimensions thus, it is selected as the baseline vehicle. This is because additional payload would enable accommodation of components or medical equipment while longer length (137 inches) and height (76 inches) would provide more room for the patient compartment. Figure 10 shows the overall vehicle dimensions of Ranger 6×6 800: length, height, and cab to axle.

Figure 10. Overall dimensions of Polaris Ranger 6×6 (height and lengths) [51]

In addition to the overall vehicle dimensions, the floor configuration of the baseline vehicle shown in Figure 11 were investigated.
With the consideration to substitute the bed box with the patient compartment, the structural layout and geometrical configurations of the frame are used to model the attachments as well as the floor arrangement. The structural layout was acquired via electronic manual, 2012 while geometrical dimensions were measured from an older model, 2009 [51][57]. Upon selecting the baseline vehicle and identifying the required physical dimensions and floor arrangement for establishing the geometry of the patient compartment, space frame material and suitable fabrication method is identified.

**Selecting structural materials for the patient compartment.** In comparison to developed countries, the availability, manufacturability, and maintainability of structural materials are limited in cost and in skills thus, even though the standard document specifies aluminum materials, common materials like steel with basic shapes such as round tubes and square tubes were identified as suitable structural properties for rural SSA. Since specific grade(s) of the chassis couldn’t be confirmed by any of the consulted representatives, the mechanical properties of low-alloy steels were deemed appropriate for design configurations. And, for assembly, it was decided that welding steel space frame elements was a feasible method in providing adequate structural support and maintenance in low-income areas. To minimize corrosion, it was decided the frame would be coated
using local metal paints like red oxide primer. Hence it was deduced that the selected baseline vehicle, Polaris Ranger 6×6 800 along with the selected material, steel would provide adequate framework for designing and evaluating the patient compartment.

**Designing and Analyzing Models of the Patient Compartments**

Upon developing the strategy to transform the shoulder girdles to bio-mimicked columns and establishing geometrical as well as structural specifications of the patient compartment, bio-mimicked and box frame models are created and analyzed for geometrical advantage. The frames are modelled via DesignModeler in ANSYS where geometrical configurations and material properties are defined. Both models are analyzed for static and impact performances in Projects via ‘Static Structural’ and ‘Explicit Dynamics’ also in ANSYS [21]. For static analysis, body loads are defined in x, y, and z directions and solved via Mechanical APDL and for side and rear impact analysis, deformations are obtained via AUTODYN using moving barriers that are deformable and rectangular in shape. The results are post-processed by capturing the structural failures as contour maps of deformations in inches (in), stress values in psi, and energy as BTU.

**Modelling bio-mimicked and box frame patient compartments.** With the intent of safely accommodating a ‘primary patient’ on a wheeled cot, patient compartments were configured using the dimensions of the baseline vehicle and the standard document. The overall dimensions (length, width and height) of the baseline vehicles as well as the floor layout Figure 10. Overall dimensions of Polaris Ranger 6×6 (height and lengths) [51] were used to configure the volume of the frame structure and the attachment points of the beam-columns. The frame was configured to the patient’s cot (22 inches in width and 79 inches in length) by providing a 5 inch space around the cot to allocate adequate working space
without jeopardizing the overall width of the vehicle (60 inches) or the allowable body length (94 inches). It was imperative that the overall height of the vehicle be maintained at 76 inches so as to avoid increasing the center of gravity. By doing so, the height from the floor of the frame to the roof was estimated to be 56 inches which is slightly less than the required height, 60 inches. Additionally, while the standard requires a minimum length of 122 inches, it was critical not to dimension the length of the frame beyond 94 inches i.e. 2x47 (47 inches is cab to axle). By adding 10 inches to the length of the cot (79 inches), it was considered that the designed length 94 inches was acceptable for the patient compartment. Table 4 shows a summary of geometrical dimensions of the tortoise, the ambulance vehicle (ASTM), Polaris vehicle and the patient compartment.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Tortoise’ Trunk (inches)</th>
<th>Ambulance Vehicle (inches)</th>
<th>Polaris Vehicle (inches)</th>
<th>Patient’s Frame (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>7.3</td>
<td>122</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Width</td>
<td>3.4</td>
<td>62</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>Height</td>
<td>2.4</td>
<td>60</td>
<td>56</td>
<td>56</td>
</tr>
</tbody>
</table>

After the overall width, length, and width of the frame to the patient compartment were estimated, the geometry of the bio-mimicked columns were iterated and proportioned within the perimeter of the length, width and height configurations. For comparison purposes, another patient compartment but with box configuration was modelled within the envelope of the overall dimensions. The box frame was modelled via geometrical points locating center to center dimensions to a height of 53.47 inches, width of 46.73 inches and
lastly, a length of 85 inches. With the aim to obtain similar geometry, the center to center dimensions of the bio-mimicked model were, 53.35, 47.84 and 85 inches respectively.

Analyzing bio-mimicked and box frame patient compartments. After the bio-mimicked columns were scaled to the derived parameters (length, width and height), default generic steel properties defined as ‘structural steel’ of yield strength 36,259 pound-force per square inch (psi) and ultimate strength of 66717 psi were assigned to all frame models via ANSYS workbench. Since it is assumed that the designed model will be fabricated and maintained in rural SSA, low-alloy welded steel materials i.e. AISI and proprietary grades were selected for the frame body as opposed to the recommended materials, aluminum (Table 2) [8]. Following after, tube dimensions were obtained from online distributors (Steel Makers, Tarmal Steel and Brollo Kenya) where round tubes with various inner and outer diameters: 0.975 – 1.000, 1.084 - 1.250, 1.588 - 1.750, and lastly, 1.624 - 2.000 were iterated to identify the optimal geometrical dimensions [2] [5] [6]. The National Hot Rod Assembly (NHRA) recommends an outer diameter of 1.75 inches and a thickness of 0.118 inches for mild steel or 0.065 inches for AISI 4130 [1]. In this study however, an outer diameter of 1.25 inches and a wall thickness of 0.083 inches was assigned to the bio-mimicked frame as well as the comparison box frame as a worst case design strategy. After assigning structural properties to both models, static analysis was conducted by defining body loads in x, y, and z directions via Mechanical APDL. Side and rear impact analysis were also performed via AUTODYN using moving barriers that are deformable and rectangular in shape.

Static Structural analysis of the frame models - box and bio-mimicked. Structural analysis was conducted in three stages: static analysis of the bio-mimicked frame
and box frame (four columns), static and impact analysis of the bio-mimicked frame and box frames with additional columns, (six in total) and, static and impact analysis of the bio-mimicked frame and box frame configured to the floor elements of Polaris’ chassis floor (six columns). Two support elements are added to the floor chassis so as to match the beam-columns with support conditions/attachments.

**Static analysis of bio-mimicked and box frames.** The processed models, bio-mimicked and box frames were analyzed as beam elements. Gravitational loads, 386.09 in/s² or 32.2 ft/s² were applied downwards and sideways with supports at four corners so as to evaluate the performance of the models under their respective body weight, 62.65 lbs. for box and 65.76 lbs. for bio-mimicked frame. The set-ups for both frames, in z directions (rear sides) are shown in Figure 12.

![Figure 12. Bio-mimicked and box frame set-ups for gravitational accelerations (Z)](image)

In addition to the gravitational load, nine more iterations were conducted using the same set-up but increasing the body load while ensuring that structural failures are within the elastic region i.e. stress value below 36,259 psi. Stress values; direct stress, minimum and maximum combined stress along with the total deformations in inches, were captured and
presented as contour maps in forms of figures. Stress limits in x and z directions for both models were iterated at various loadings and are presented as figures.

**Static analysis of the bio-mimicked frame and box frames with additional columns - box and bio-mimicked model.** By investigating the influence of body loads in y, x and z directions, it was realized that largest stress values on both frames occurred in z directions. Additionally, by linearizing loads and stress values in y direction for both models, maximum load conditions within the yield strength for z directions were estimated to be 5,938 in/s² and 6,047 in/s² for bio-mimicked and box frames respectively. Thereafter, additional support elements (two) were evenly added evenly to the bio-mimicked frame as well as the box frame on each side to observe the structural behavior of both models using similar columns i.e., beam-column for bio-mimicked frame and relatively straight columns for the box frame. Simple supports and maximum body loads of 1,527.8 lbs. and 1,377.1 lbs. within the yield strength were applied in +z for the bio-mimicked model as well as the box model as illustrated in Figure 13. The body loads

![Figure 13. Bio-mimicked and box frames with added columns under acceleration loads (Z)](image-url)
Static analysis of the bio-mimicked frame and box frame configured to the floor elements of Polaris’ chassis floor. Given that the frames are to be mounted on the floor chassis of Polaris Ranger, the support elements for both frame models were shifted so as to match the beam elements. And, for comparison purposes, similar supports (simple) and loads (1,400 lbs.) were applied to both models so as to evaluate their structural performances as illustrated in Figure 14.

![Figure 14. Bio-mimicked and box frames with adjusted columns under acceleration loads (Z)](image)

Impact analysis of the frame models - box and bio-mimicked. After analyzing the structural frames under varying body loads, AMD S.6, FMVSS 301 and FMVSS 214 were used as guiding standards for impact analysis. Dynamic simulations were conducted using rectangular deformable (AL 2024-T4) barriers that were moving at 528 in/s (30 mph) and 589.6 in/s (33.5 mph) and, weighed 1,831 lbf and 3,098 lbf for rear impacts and side impacts for each models as illustrated in Figure 15 and Figure 16.
The structural failures of the frames are represented as contour maps of deformations while the stability of the simulations are monitored through the ‘energy error’ values, less than 10% via charts on energy conservation and also the presence of ‘contact energy’ or sliding energy via charts on the charts of energy summary. In the first set of simulations, bio-mimicked and box frames with four columns are stationed via simple supports at the end nodes and rear impacts lasting 0.0075 seconds and side impacts lasting 0.01 seconds are conducted in ANSYS via AUTODYN. The selected durations, 0.0075 and 0.01 seconds were based on iterations with stable values i.e. with less than 10% energy error on both bio-mimicked and box frame models. Thereafter, side impacts simulations were performed.
on bio-mimicked and box models with additional support columns that are adjusted to the beam elements of Polaris’ floor chassis. Due to the rear configuration of the bio-mimicked model, angular in shape, significant energy error was observed on the four columns frame as such, box and bio-mimicked comparisons of the rear impacts with additional and adjusted columns were not conducted. However, it was noticed that stable side and rear impact results could be obtained by enclosing the bio-mimicked frame with ‘A’ like supports on both ends. The configuration with the additional, the adjusted as well as the enclosed support elements was considered as the finalized bio-mimicked frame model for the patient compartment model. The finalized bio-mimicked model was analyzed to observe performance variations with addition of beam-columns. By adding the ‘A’ like members into the bio-mimicked configuration, the criteria of comparison changed as the model wasn’t fully bio-mimicked. Thus, a finalized box configuration i.e. with additional support columns that are adjusted to the beam elements of Polaris’ floor chassis wasn’t modelled or analyzed.
RESULTS

Acquired and deduced data is presented in three categories, quantitative, descriptive and qualitative. In the quantitative section, physical models of the bio-mimicked frame, box frame and Polaris floor chassis are presented as well as the finite elements models of both frames under static and dynamic evaluations. In the descriptive section however, summarized values of finite element models are illustrated in tables and charts with linearized equations. In the last section, qualitative information on the baseline vehicle and the structural elements as employed in emergency service vehicle for rural SSA and bio-mimicry strategy are provided.

Quantitative Data - Box Models and Bio-Mimicked Models

Geometrical Configurations. The models of the bio-mimicked and box frames are shown in Figure 17 and Figure 18 and the corresponding properties are listed in Table 5.

![Figure 17. Physical model of the bio-mimicked frame, front and right side views](image)
Table 5. The physical properties of bio-mimicked and box frame models

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Bio-Mimicked Model</th>
<th>Box Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass, lbm</td>
<td>65.8</td>
<td>62.7</td>
</tr>
<tr>
<td>Volume, inches³</td>
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<td>85.0, 46.7, 53.5</td>
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For compatibility, Polaris Ranger’s floor chassis was modeled along with the basic configuration of the bio-mimicked frame as illustrated in Figure 19.

Static analysis of the frame models. Static structural failures of both models as simple bio-mimicked and box frames, and also, as frames with additional support structures
as well as frames with adjusted beam-columns to align with the beam elements of Polaris floor chassis are presented via figures illustrating the total deformations in inches and stress values in psi as contour maps.

**Static analysis of bio-mimicked and box frames - standard earth loads.** The total deformations and the maximum combined stress of both frames under gravitational loads in x (width), y (height), and z (length) directions are presented in Figure 20 through Figure 25.

**Total deformations in x direction.** The largest total deformations are observed on the roof beams, 0.086 inches for bio-mimicked model and 0.117 inches for the box model. Also, it is observed that both configurations have similar stress patterns on the beams, columns, and joints.

![Figure 20. Total deformations on bio-mimicked and box frames - earth load, x](image)

**Total deformations in y direction.** For the box frame, largest deformations, 0.014 inches are observed on both the roof beams and the floor beams while for the bio-mimicked model, the largest deformations (0.015 inches) are observed only on the roof beams as the floor beams have minimum deformations. In both configurations, the joint locations have minimum deformations.
Total deformations in z direction. Both frames appear to have similar deformation patterns but larger deformations, 0.171 inches are observed on the roof beams of the box frame, compared to the roof beams of the bio-mimicked frame, 0.109 inches.

Maximum combined stress in x direction. On both frames, largest stress values are observed at the support locations, 2,082 psi for the bio-mimicked frame and 2,056 psi for the box frame. Also, larger stress values are observed on the columns of both configurations than the beams. However, the ‘inner’ columns of the bio-mimicked frame
and the corresponding joints have minimum stress values from 22 psi at the mid-region to 251 psi at the joints.

Figure 23. Max. combined stresses of bio-mimicked and box frames - gravity load (X)

*Maximum combined stress in y direction.* While it is observed that both frames have very close maximum stress values, 429 psi for bio-mimicked model and 428 psi for the box model, the contours show that the box model has largest stress values on the roof beams as well as the floor beams but bio-mimicked’ largest deformations are only observed on the roof beams. Additionally, there are maximum stress values at the floor joints of the box model and reduced stress, 210 psi at the floor joints of bio-mimicked model.

Figure 24. Max. combined stresses of bio-mimicked and box frames - gravity load (Y)
Maximum combined stress in z direction. It is observed that the largest maximum combined stresses occur on the floor beams near the support points for the box frame and slightly away from the support points for the bio-mimicked frame i.e. at the ‘third’ column. It is also observed that the support columns of the bio-mimicked frame consist of lower stress values that range from 1,290 psi to -45 psi (compression) compared to the support columns of the box frame, 0 psi and 2,315 psi (almost double of bio-mimicked maximum stress).

Figure 25. Max. combined stresses of bio-mimicked and box frames - gravity load (Z)

Static analysis of bio-mimicked and box frames - added columns. The total deformations and the maximum combined stress of bio-mimicked and box frames with additional support structures under body loads 1,527 lb and 1,377 lb respectively in y direction are presented in Figure 26 and Figure 27.

Total deformations. With the even addition of four columns on both models, while the failure patterns are similar to the initial configurations it is observed that the deformation values for the box frame model (loaded at 1,377 lb) are 2.4 times higher than the bio-mimicked model (loaded at 1,527 lb). Without additional columns and load, the largest deformation of the box model was 1.6 times larger than the bio-mimicked model.
Maximum combined stress. With eight columns, it is observed that the stress values for the box frame are 2.4 times higher than the bio-mimicked model. Also, for the bio-mimicked model, unlike the four columns, largest stress values (12,520 psi) are also observed on the columns by the roof beams as well as on the mid-sections of the outer columns. And for the box model, while the largest stress values (30,913 psi) are not observed at the attachment points, they appear to be concentrated on the lower and upper ends of the mid columns (added columns).

Static analysis of bio-mimicked and box frames - adjusted columns. The total deformations and the maximum combined stress of bio-mimicked and box frames with
additional support structures that are aligned with the beam elements of the chassis under similar body loads 1400 lb in all directions are presented in Figure 28 through Figure 33.

**Total deformations in x, y, and z directions.** When the added columns are shifted to the match the beam elements of the Polaris’ chassis and subjected to equal loadings (1,400 lb) in all directions, it is observed that the bio-mimicked frame deforms less than the box frame by 2.1 times in x, 5.4 in y and 2.3 in z directions. The contours in both frames show similar patterns with the largest deformations on the roof beam-columns that are furthest apart.

---

**Figure 28. Total deformation on bio-mimicked and box frames - 1400 lb body load, x**

**Figure 29. Total deformation on bio-mimicked and box frames - 1400 lb body load, y**
Figure 30. Total deformation on bio-mimicked and box frames - 1400 lb body load, z

Maximum combined stresses in x, y, and z directions. It is observed that under 1,400 lb body load in x direction, the stress values for both bio-mimicked (46,149 psi) and box frames (52,090 psi) exceed the yield strength, 36,259 psi but still fall within the ultimate strength (66,717 psi). But, in y direction the stress values for both frames are within the elastic limit however, the stress values for the box model are higher (27,615 psi) than bio-mimicked model (14,185 psi). And in z direction, it is observed that the box frame fails (41,784 psi) while the max. combined stress value for the bio-mimicked model is 17,299 psi. Additionally, with the exception of the frame models under body loads in z direction, it is observed that the largest stresses mostly occur on the floor beams of both frame models near the front in x direction and towards the middle in y direction. In addition to the floor beams, it is also observed that large stress values occur on the roof beams of the box frame in y direction. And, in z direction, largest stress values are observed on the lower ends and upper ends of the 2nd columns from the front on both models. However, for the box model, the largest deformation on the lower end of the column occurs at the support locations.
Figure 31. Max. combined stress on bio-mimicked and box frames - 1400 lb body load, x

Figure 32. Max. combined stress on bio-mimicked and box frames - 1400 lb body load, y

Figure 33. Maximum combined stress on bio-mimicked and box frames - 1400 lb body load, z
Impact analysis of the frame models. Dynamic structural failures of both models as simple bio-mimicked and box frames, and also, as frames with additional support structures as well as frames with adjusted beam-columns to align with the beam elements of Polaris floor chassis are presented via figures illustrating the total deformations in inches as contour maps.

Rear impact analysis of the bio-mimicked and box frames. Due to the angular configuration of the bio-mimicked frame, it is observed that the bio-mimicked model deforms slightly less than the box model, 1.311 inches compared to 2.004 inches. It is also shown in Figure 34 that the bio-mimicked model has less deformed areas (roof beams) than the box frame (roof beams, rear columns, and rear floor beam).

Figure 34. Total deformations on bio-mimicked and box frames as four columns - rear impact

Side impact analysis of bio-mimicked and box frames. Similarly, for the side impacts, it is observed that in addition to the bio-mimicked frame deforming slightly less than the box model, 1.321 inches compared to 1.351 inches that the areas of impact (mid-
section of the side columns) are less than of the box model (mid-sections of the side columns and the side floor beam) as shown in Figure 35 and Figure 36.

Figure 35. Total deformations on bio-mimicked and box frames as four columns - side impact, isometric view

Figure 36. Total deformations on bio-mimicked and box frames as four columns - side impact, front view

Rear impact analysis of bio-mimicked and box frames with additional support elements configured to Polaris’ chassis. It is observed that with increased impact time, 0.01 to 0.02 seconds the barrier further deforms the bio-mimicked frame to a maximum deformation of 4.772 inches that mostly occur on the roof compared to the box model
which deforms to 6.439 inches on the floor beams and up to 7.727 inches on the rear columns as well as the roof beams.

Figure 37. Total deformations on bio-mimicked and box frames with adjusted columns - rear impacts

Side impact analysis of bio-mimicked and box frames with additional support elements configured to Polaris’ chassis. While the time of impact is slightly higher than the basic configuration, 0.01 vs 0.0075 seconds, Figure 38 shows that the deformation patterns are similar in that, in addition to the bio-mimicked columns deforming less than the box columns, (4.589 inches vs 5.013 inches) they mostly deform midway to upwards leaving majority of the floor non-deformed.

Figure 38. Total deformations on bio-mimicked and box frames with adjusted columns - side impacts
**Rear impact analysis of the finalized frame model as the bio-mimicked patient compartment.** With twice the duration of impact, it is observed that by enclosing the bio-mimicked model with ‘A’ like members, the largest deformations, 8.112 inches mainly occur on the roof beams while and the lowest deformations, 0 inches occur on the floor beams just like in the added and adjusted columns with half the impact duration 0.01 seconds and almost half the largest deformations, 4.772 inches on the roof beams and upper columns and 0 inches on the floor beams and lower columns.

![B: Bio Full Model Rear Impact 0.01s](image)

Figure 39. Total deformations on bio-mimicked rame as a potential finalized frame - rear impact

**Side impact analysis of the finalized frame model as the bio-mimicked patient compartment.** Given that both bio-mimicked models, adjusted columns (Figure 38) and enclosed columns (finalized) are subjected to similar impact conditions, Figure 40 shows a deformation of 4.597 inches which is relatively close to 4.589 inches of the eight columns model are observed.
Figure 40. Total deformations on bio-mimicked frame as a potential finalized frame - side impact

Descriptive Data on Body Loads and Impact Loads

Gravitational loads, 386.09 in/s² in x, y and z directions.

Table 6. A summary of the minimum and maximum values of bio-mimicked and box models under earth’s gravity in x, y and z directions.

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<th>Overall Frame Structure</th>
<th>BIO (x)</th>
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Body Loads, 386.09 in/s² to 3860.9 in/s² applied in y direction

Figure 41. Minimum combined stress vs acceleration loads (Y) of the bio-mimicry frame model

Figure 42. Minimum combined stress vs acceleration loads (Y) of the box frame model

Body loads, 1400 lbf on additional and adjusted supports.

Table 7. A summary of the minimum and maximum values of bio-mimicked and box models under 1400 lbf in x, y and z directions.

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<tr>
<th>Overall Frame Structure</th>
<th>BIO (x)</th>
<th>BOX (x)</th>
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Table 8. Static structural values of adjusted columns, radii 0.792 and 0.875 inches radii under 1400 lb (X)

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<td>-559</td>
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Qualitative Data

**Baseline vehicle.** By assuming that the selected utility vehicle, Polaris Ranger 6×6 800 will be used in developing the ambulance vehicle, it is deduced that the modeling of the bio-mimicked frame around a primary cot would provide additional volume around the patient’s cot thereby enabling transportation of patients in a lateral position as opposed to the sitting/inclining (non-ergonomic) positions on bicycle and motorcycle ambulances. In addition to geometrical advantages, it is implied that the off-road capability of the utility vehicle will reduce transportation delays and, increase the ride quality while in transit which will enable timely and safely arrival of patients and drivers.

**Bio-Mimicked and box model structural columns.** During configuration, it is observed that the orientation (slanting/curvature) of the bio-mimicked columns as well as ‘trigonal’ effect provides additional volume at the required regions i.e. around the patient’s cot compared to the straight columns in the box like arrangement which would require increasing the entire width of the frame. Also, unlike the box frame structure, it appears that the ‘trigonal’ beam-columns provide an outer and inner layer like boundary elements at the base of the compartment which could imply a ‘safe’ space provision for the outer column for instance, to deform inward without intruding into the occupants space.
DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

The models configured, analyzed and evaluated are discussed and the conclusions on the architectural leverage of the bio-mimicked columns in chassis design of an ambulance body are presented along with potential future research areas in structural design optimization.

Discussion

The designed structural models, bio-mimicked frame and the box frame, as well as the estimated model, Polaris floor chassis are discussed in structural configurations along with the static and dynamic failures of the finite element models as basic configurations (four columns) and also, as adjusted configurations (additional and aligned support elements with the beam elements of the floor).

Structural configurations. Even though the allometry of the shoulder girdles was captured and configured to the beam columns, additional columns were added within the original configuration for structural support and also outside for functionality. On the other end, for the box frame, a random and a general configuration was used as such, the comparisons to other box like configurations might differ from the one presented in this investigation. And, for the Polaris floor chassis, even though the dimensions of the selected model, 2014 weren’t accessible, geometrical estimates were obtained by synthesizing actual measurements of a previous model (2009) and the specifications of the manual (2012). Since then, a new model with an ‘A’ like configuration is available in the market.

Structural performances.

Basic configurations, standard gravitational loads (x, y, and z). When both models are subjected to standard gravitational loads, it is observed that bio-mimicked
frames deform slightly less than the box frame in x and z directions and that the largest deformations on both models occur on the roof beams. However, in the y direction, it is observed that the roof beams of the box frame and the floor beams deform the most and also in a similar manner while for the bio-mimicked frame, only the roof beams deform while the floor beams mostly remain un-deformed. And, by looking at the maximum combined stresses, it is seen that in the x direction, largest deformations on the box frame mainly occur on the upper (roof) and the lower (floor) ends of the columns as well as the ends of the floor beams while for the bio-mimicked frame although slightly larger than the box frame, the largest deformations are mainly observed on the ends of the floor beams.

However, in the y direction, both models have relatively equal maximum values on the roof beams and the upper ends of the columns for the bio-mimicked frame and for the box frame, in addition to the roof beams and upper ends of the columns, largest stress values are also observed on the floor beams. Lastly, in the z direction, the largest maximum combined stress values only occur on the floor beam of the bio-mimicked frame by the ‘third’ column but for the box frame, while largest stress values are observed on the floor beams, relatively large values are also seen on the upper ends of the columns as well as the ends of the roof beams.

**Adjusted configurations, body load, 1400 lbs.** By increasing the load, adding similar support members and shifting the beam-columns to the beam configurations of the baseline vehicle, the deformation patterns are observed to be similar in all directions where largest deformations occur on the roof in particular, the last pair of columns. It is also observed that the deformation values of the bio-mimicked frame are less than the values of the box frame, 2.07 times in the x direction, 5.4 times in the y direction and 2.25 times in
the z direction. But, by looking at the maximum combined stress values, the contour maps show that in the x direction, both frames deform similarly where the (front) ends of the floor beams fail beyond the yield strength (36,259 psi) to 46,149 psi and 52,090 psi for bio-mimicked and box frames respectively. And in the y direction, almost twice the stress values of bio-mimicked frame are observed on the box frame. Additionally, largest stresses are observed on the floor and roof beams of the box frame as opposed to just the floor beams on the bio-mimicked frame.

Basic and adjusted configurations, Rear Impact. With the short duration of the rear impact on a basic configuration, the roof beams, mid columns as well as the floor beam of the box frame model deforms slightly more than the roof beams and the upper ends of the bio-mimicked columns. By doubling the duration of impact and adding support columns that are aligned with the beam elements of chassis, the deformation patterns were observed to be similar where bio-mimicked model mainly deformed from the roof downward to the columns while the box frame deformed from the roof and also the columns.

Basic and adjusted configurations, Side Impact. Just like in rear impact analysis, it is observed that the bio-mimicked frame deforms slightly less than the box frame. It is also seen that smaller portions of the bio-mimicked columns (mid outer column) consist of largest deformations while for the box frames, the largest deformations are observed on majority of the columns as well as the floor beam. And, when the time of impact is slightly increased and support structures are added and aligned with the beam elements of the chassis of Polaris Ranger, the deformation criteria for both models are observed to be similar to the basic configuration but with slightly higher values where the box model
deforms the most, at the columns, the roof and the floor beams while the bio-mimicked columns largely deform at the mid-section.

**Conclusions**

Even though geometrical requirements of the patient compartment were constrained by the baseline vehicle, through bio-mimicry strategy, the arrangement of the ‘trigonal’ beam-columns added functional volume around the patient’s cot while keeping heavier mass towards the bottom. And, in combination with the structural performances under static loadings, it appears that the ‘third’ column functions as a stress dissipater for the bio-mimicked frame. For instance, during body loads in the y directions, maximum deformations and stresses are observed on the roof beams, the floor beams as well as the mounting joints of the box frame but, for the bio-mimicked frame minimum deformations and stress values are observed on the floor beams and the support locations. In impact loadings, while it is understood that the shape of the barrier has an influence on the results, it is deduced that for a rectangular or block configuration, the angular layout of the bio-mimicked frame at the rear contributes to reduced travel distance during deformation while the outer and inner like configurations of the ‘trigonal’ beam-columns provide an impact like space such that, as the ‘outer’ like columns deform during side impacts, the ‘inner’ or ‘third’ column absorbs some of energy while preventing the outer column from deforming into the occupant’s space.

Thus it is concluded that bio-mimicked support elements added structural volume and structural rigidity to the patient compartment at areas surrounding the patient’s cot as well as stress relief at joints and floor mounting locations. Hence, by employing the bio-mimicked patient configuration in an ambulance vehicle, functional volume could be
utilized in administering emergency services during transit and, accommodate additional safety and medical functions for the vehicle like energy absorbing materials in case of collisions or medical equipment and supplies. Also, the stress dissipater function by the ‘third’ column on the floor beams would minimize failures at the joints during side or rear impacts improving the crashworthy of the bio-mimicked ambulance vehicle.

**Recommendations**

Results on static structural performances indicate that in all directions, box-configuration deform at least twice as the bio-mimicked configuration. The deformations during side and rear impacts of the box frames are observed to be slightly more than the bio-mimicked frames. Impact results also show that larger deformations occur on the columns as well as the floor and the roof beams of the box models while the floor beams of the bio-mimicked models incur minimal deformations. Since both compartments were simulated as components, it is recommended that assembly simulations be conducted to monitor static, impact and roll-over structural performances of both configurations under expected joint conditions such as modelling bolt holes, defining welded joints and bolt loadings.
APPENDIX A - BIBLIOGRAPHY


[48] Animal Life Encyclopedia, Reptilia


APPENDIX B - PERMISSION TO CONDUCT RESEARCH
APPENDIX C - DATA COLLECTION DEVICE
C1 Computations in MATLAB

Numerical Analysis Contents

NURBS' Value Points of Scapular Prong & Acromial Process

Formulation of the Best-Fit Plane

Sketching Best-Fit Plane and Curve of Scapular Prong & Acromial Process

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NURBS' Value Points of Scapular Prong & Acromial Process

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Formulation of the Best-Fit Plane

s=size(datamatrix);

n=s(1); %number of data points

x=datamatrix(:,1);
y=datamatrix(:,2);
z=datamatrix(:,3);

% Centroid of the curve's point masses

N=n-1; %number of weighted data points

for i=1:N
    w(i)=sqrt((x(i+1)-x(i))^2+(y(i+1)-y(i))^2+(z(i+1)-z(i))^2);
end %endfor

M=sum(w); %mass

for i=1:N %Locations of weighted points, @ midpoints of the segments

\begin{verbatim}
XX(i) = (x(i) + x(i+1))/2;
YY(i) = (y(i) + y(i+1))/2;
ZZ(i) = (z(i) + z(i+1))/2;
end %endfor

Myz = dot(w, XX); %Computation of moments
Mxz = dot(w, YY);
Mxy = dot(w, ZZ);

xbar = Myz / M; %Computation of the centroid
ybar = Mxz / M;
zbar = Mxy / M;

centroid = [xbar ybar zbar]'

X = x - xbar; %new coordinates, so centroid goes through the 'origin'
Y = y - ybar;
Z = z - zbar;

%Normal vector <v> minimizes sum of weighted squared distances to the plane

% Second moments:
Sxx = dot(w, (X(1:n-1).*X(1:n-1) + X(1:n-1).*X(2:n) + X(2:n).*X(2:n))) / 3;
\end{verbatim}
Syy = \dot{w}, (Y(1:n-1).*Y(1:n-1)+Y(1:n-1).*Y(2:n)+Y(2:n).*Y(2:n))/3

Szz = \dot{w}, (Z(1:n-1).*Z(1:n-1)+Z(1:n-1).*Z(2:n)+Z(2:n).*Z(2:n))/3

% Sxy = \dot{w}, (X(1:n-1).*Y(2:n)+X(2:n).*Y(1:n-1)+...
     2*X(1:n-1).*Y(1:n-1)+2*X(2:n).*Y(2:n))/6;

Sxz = \dot{w}, (X(1:n-1).*Z(2:n)+X(2:n).*Z(1:n-1)+...
     2*X(1:n-1).*Z(1:n-1)+2*X(2:n).*Z(2:n))/6;

Syz = \dot{w}, (Y(1:n-1).*Z(2:n)+Y(2:n).*Z(1:n-1)+...
     2*Y(1:n-1).*Z(1:n-1)+2*Y(2:n).*Z(2:n))/6;

%

Q = [Sxx, Sxy, Sxz;
    Sxy, Syy, Syz;
    Sxz, Syz, Szz];

[u s vv] = svd(Q);

% Eigenvalues of Q are the singular values

% Vectors in u and v are the eigenvalues

% svd is used instead of eig as svd orders the singular values

% The unit normal vector of the least-squares best fit plane is vv

v = vv(:,3);

normalVector = v

centroid =
Sketching Best-Fit Plane and Curve of Scapular Prong & Acromial Process

```matlab
for i=1:N % Line segments connecting adjacent points
    plot3([x(i) x(i+1)], [y(i) y(i+1)], [z(i) z(i+1)])
    axis('equal')
    hold on
end %endfor

v2=vv(:,2);
v3=vv(:,1);

A=ones(n,1)*[xbar,ybar,zbar]; % n by 3
B=datamatrix-A;
dotprodmatrix=B*v2; %N by 1
absmatrix=abs(dotprodmatrix);
```
v2halfwidth=6/5*max(absmatrix);

A=ones(n,1)*[xbar,ybar,zbar]; % n by 3

B=datamatrix-A;

dotprodmatrix=B*v3; % n by 1

absmatrix=abs(dotprodmatrix);

v3halfwidth=6/5*max(absmatrix);

if (v3halfwidth < v2halfwidth) %switch v2 & v3
    temp = v2;
    v2=v3;
    v3=temp;
    temp=v2halfwidth;
    v2halfwidth=v3halfwidth;
    v3halfwidth=temp;
end % Plane is as long in v3-direction

NN=5; %determines how many lines will be in grid for plane

side=v2halfwidth/NN; %length of a side of a square

K=floor(v3halfwidth/side); %there'll be 2*K boxes in shorter direction,
                                %2NN boxes in longer direction

%create arrays with coords of points along boundary of rectangle for plane:
A1 = side * (-NN:NN)' * v2';

A1 = A1 + ones(2 * NN + 1, 1) * [xbar, ybar, zbar];

A2 = A1;

A1 = A1 - K * side * (ones(2 * NN + 1, 1) * v3');

A2 = A2 + K * side * (ones(2 * NN + 1, 1) * v3');

B1 = side * (-K:K)' * v3';

B1 = B1 + ones(2 * K + 1, 1) * [xbar, ybar, zbar];

B2 = B1;

B1 = B1 - NN * side * (ones(2 * K + 1, 1) * v2');

B2 = B2 + NN * side * (ones(2 * K + 1, 1) * v2');

% for i = 1:2 * NN + 1

    plot3([A1(i, 1) A2(i, 1)], [A1(i, 2) A2(i, 2)], [A1(i, 3) A2(i, 3)], 'Color', [0.1 0.8 0.2])

    % axis("equal") % doesn't work

    hold on

end % endfor

for j = 1:2 * K + 1

    plot3([B1(j, 1) B2(j, 1)], [B1(j, 2) B2(j, 2)], [B1(j, 3) B2(j, 3)], 'Color', [0.1 0.8 0.2])

    hold on
title('Best-Fit Plane-Scapular Prong & Acromial Process-Leopard Tortoise')
xlabel('X-Coordinate(mm)')
ylabel('Y-Coordinate(mm)')
zlabel('Z-Coordinate(mm)')
end %endfor
hold off
<p>| D1  | Requirements Traceability Matrix (RTM) [CORE, SDD] |</p>
<table>
<thead>
<tr>
<th>Allocated Capabilities/Requirements</th>
<th>Traced From Higher-Level Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS All-Terrain Vehicle Ambulance (Component)</td>
<td></td>
</tr>
<tr>
<td>TT _Perform Testing Functions (Function)</td>
<td></td>
</tr>
<tr>
<td>7.4 Tests: (Requirement)</td>
<td>7 Quality Assurance Provisions (Requirement)</td>
</tr>
<tr>
<td>TT.4 Tests (Function)</td>
<td>7.4 Tests: (Requirement)</td>
</tr>
<tr>
<td>TT.4.2 Performance Tests (Function)</td>
<td>7.4.2 Performance Tests (Requirement)</td>
</tr>
<tr>
<td>TT.4.2.1 Physical Dimensions (Function)</td>
<td>7.4.2.1 Ambulance Physical Dimensions (Requirement)</td>
</tr>
<tr>
<td>TT.4.2.2 Weight Distribution (Function)</td>
<td>7.4.2.2 Vehicle Weight Distribution (Requirement)</td>
</tr>
<tr>
<td>TT.4.2.3 Road Tests (Function)</td>
<td>7.4.2.3 Road Tests (Requirement)</td>
</tr>
<tr>
<td>TT.4.2.10 Body Structure (Ambulance) (Function)</td>
<td>7.4.2.10 Ambulance Body Structure (Requirement)</td>
</tr>
<tr>
<td>TT.4.2.11 Patient Compartment (Interior Surfaces) (Function)</td>
<td>7.4.2.11 Patient Compartment Interior Surfaces (Requirement)</td>
</tr>
<tr>
<td>SS.1 Vehicular Design, Types and Floor Plans (Component)</td>
<td></td>
</tr>
<tr>
<td>SS.1.1 _Perform Design Functions (Function)</td>
<td>6.1.1 Design (Vehicle) (Requirement)</td>
</tr>
<tr>
<td>SS.1.2 _Perform Type 1 Ambulance Functions (Function)</td>
<td>6.1.2 Type I Ambulance (Requirement)</td>
</tr>
<tr>
<td>SS.1.5 _Perform Patient Configuration Functions (Function)</td>
<td>6.1.5 Configuration of Patient Compartment (Requirement)</td>
</tr>
<tr>
<td>SS.1.6 _Perform Chassis 4WD Functions (Function)</td>
<td>6.1.6 Four Wheel Drive, Class 2 4 × 4: (Requirement)</td>
</tr>
<tr>
<td>6.1 General Vehicular Design, Types and Floor Plan (Requirement)</td>
<td>6 Requirements (Requirement)</td>
</tr>
<tr>
<td>SS.1.1 Design (Component)</td>
<td></td>
</tr>
<tr>
<td>SS.1.1.1 Design Operability (Function)</td>
<td>6.1.1.1 Operability (Requirement)</td>
</tr>
<tr>
<td>SS.1.1.2 Design Functionability (Function)</td>
<td>6.1.1.2 Functionability (Requirement)</td>
</tr>
<tr>
<td>SS.1.1.3 Design Serviceability (Function)</td>
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</tr>
<tr>
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<td>6.1 General Vehicular Design, Types and Floor Plan (Requirement)</td>
</tr>
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<td>Traced From Higher-Level Elements</td>
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<td>SS.1.2.1 Additional Duty Ambulance (Neonatal) (Function)</td>
<td>6.1.2.1 Type I-AD (Additional Duty) Ambulance (Requirement)</td>
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</tr>
<tr>
<td>SS.1.5 Patient Compartment Configuration (Component)</td>
<td></td>
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<td>SS.1.5.2 Basic Life Support (Function)</td>
<td>6.1.5.2 Configuration “B” (BLS) (Requirement)</td>
</tr>
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<td>6.1.5 Configuration of Patient Compartment (Requirement)</td>
<td>6.1 General Vehicular Design, Types and Floor Plan (Requirement)</td>
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<td>6.1.6 Four Wheel Drive, Class 2 4 × 4: (Requirement)</td>
<td>6.1 General Vehicular Design, Types and Floor Plan (Requirement)</td>
</tr>
<tr>
<td>SS.2 Components, Equipment and Accessories (Component)</td>
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<tr>
<td>6.2 Vehicle Ambulance Components, Equipment, and Accessories (Requirement)</td>
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</tr>
<tr>
<td>SS.3 Materials (Component)</td>
<td></td>
</tr>
<tr>
<td>6.3 Recovered Materials (Requirement)</td>
<td>6 Requirements (Requirement)</td>
</tr>
<tr>
<td>SS.4 Operation, Performance and Physical Characteristics (Component)</td>
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<td>SS.4.11 Perform Physical Dimensions Functions (Function)</td>
<td>6.4.11 Vehicle Physical Dimensional Requirements: (Requirement)</td>
</tr>
<tr>
<td>6.4 Vehicle Operation, Performance and Physical Characteristics (Requirement)</td>
<td>6 Requirements (Requirement)</td>
</tr>
<tr>
<td>SS.4.11 Vehicle Physical Dimensions (Component)</td>
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<tr>
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</tr>
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</tr>
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<td>6.4 Vehicle Operation, Performance and Physical Characteristics (Requirement)</td>
</tr>
<tr>
<td><strong>SS.5 Weight Ratings and Payload (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.5.2 _Perform Payload Allowance Functions (Function)</td>
<td>6.5.2 Payload Allowance (Requirement)</td>
</tr>
<tr>
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</tr>
<tr>
<td>SS.5.6 _Perform Cab Axle Functions (Function)</td>
<td>6.5.6 Cab to Axle (CA) Type I and III Vehicles (Requirement)</td>
</tr>
<tr>
<td>6.5 Vehicle Weight Ratings and Payload (Requirement)</td>
<td>6 Requirements (Requirement)</td>
</tr>
<tr>
<td><strong>SS.5.2 Payload Allowance (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.5.2.3 Dual Rear Minimum Payload (Function)</td>
<td>6.5.2.3 Dual Rear Wheeled (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4 Additional Duty Payload (Function)</td>
<td>6.5.2.4 Additional Duty I (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4.1 Driver and EMT (Function)</td>
<td>6.5.2.4.1 Driver and EMT (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4.2 Patients (Function)</td>
<td>6.5.2.4.2 Patients (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4.3 Main and Portable Oxygen Cylinders, Stretchers, Cots &amp; Handling Equipment (Function)</td>
<td>6.5.2.4.3 Main Equipment (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4.4 Portable Removable Devices (Function)</td>
<td>6.5.2.4.4 Portable Devices (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4.5 Durable and Disposable Medical Items (Function)</td>
<td>6.5.2.4.5 Disposable Items (Requirement)</td>
</tr>
<tr>
<td>SS.5.2.4.9 Fire Extinguisher and Standard Equipment (Function)</td>
<td>6.5.2.4.9 Fire Extinguisher (Requirement)</td>
</tr>
<tr>
<td>6.5.2 Payload Allowance (Requirement)</td>
<td>6.5 Vehicle Weight Ratings and Payload (Requirement)</td>
</tr>
<tr>
<td><strong>SS.5.4 Weight Distribution (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.5.4.1 Right and Left Axle (Function)</td>
<td>6.5.4.1 Right and Left Axle Weight (Requirement)</td>
</tr>
<tr>
<td>SS.5.4.2 Center of Gravity (Function)</td>
<td>6.5.4.2 Center of Gravity (Requirement)</td>
</tr>
<tr>
<td>SS.5.4.3 Component and Equipment (Function)</td>
<td>6.5.4.3 Component &amp; Equipment (Requirement)</td>
</tr>
<tr>
<td>6.5.4 Weight Distribution (Requirement)</td>
<td>6.5 Vehicle Weight Ratings and Payload (Requirement)</td>
</tr>
<tr>
<td><strong>SS.5.6 Cab Axle (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.5.6.1 Cab Axle Openings (Function)</td>
<td>6.5.6.1 Openings (Requirement)</td>
</tr>
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<td>----------------------------------</td>
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<tr>
<td>6.5.6  Cab to Axle (CA) Type I and III Vehicles (Requirement)</td>
<td>6.5  Vehicle Weight Ratings and Payload (Requirement)</td>
</tr>
<tr>
<td><strong>SS.6 Chassis Power Unit and Components (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.6.1  _Perform Chassis Frame Functions (Function)</td>
<td>6.6.1  Chassis Frame (Requirement)</td>
</tr>
<tr>
<td>6.6  Chassis Power Unit and Components (Requirement)</td>
<td>6  Requirements (Requirement)</td>
</tr>
<tr>
<td><strong>SS.6.1 Chassis Frame (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.6.1.1  Chassis (Construction) (Function)</td>
<td>6.6.1.1  Construction (Chassis) (Requirement)</td>
</tr>
<tr>
<td>6.6.1  Chassis Frame (Requirement)</td>
<td>6.6  Chassis Power Unit and Components (Requirement)</td>
</tr>
<tr>
<td><strong>SS.10 Ambulance Body and Patient Area (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.10.1  _Perform Body accomodations Functions (Function)</td>
<td>6.10.1  Body Accomodations (Requirement)</td>
</tr>
<tr>
<td>SS.10.2  _Perform Cab/Patient Access Window Functions (Function)</td>
<td>6.10.2  Cab/Patient Compartment Access Window (Requirement)</td>
</tr>
<tr>
<td>SS.10.3  _Perform EMT Seating Functions (Function)</td>
<td>6.10.3  Emergency Medical Technician (EMT) Seating (Requirement)</td>
</tr>
<tr>
<td>SS.10.4  _Perform Patient Compartment Interior Dimensional Parameters Functions (Function)</td>
<td>6.10.4  Patient Compartment Interior Dimensional Parameters (Requirement)</td>
</tr>
<tr>
<td>SS.10.5  _Perform Body Construction Functions (Function)</td>
<td>6.10.5  Body, General Construction: (Requirement)</td>
</tr>
<tr>
<td>SS.10.6  _Perform Body Structure Functions (Function)</td>
<td>6.10.6  Ambulance Body Structure: (Requirement)</td>
</tr>
<tr>
<td>SS.10.8  _Perform Doors Functions (Function)</td>
<td>6.10.8  Doors (Requirement)</td>
</tr>
<tr>
<td>SS.10.10  _Perform Floor Functions (Function)</td>
<td>6.10.10  Floor: (Requirement)</td>
</tr>
<tr>
<td>6.10  Ambulance Body and Patient Area: (Requirement)</td>
<td>6  Requirements (Requirement)</td>
</tr>
<tr>
<td><strong>SS.10.1 Body Accomodations (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.10.1.1  EMT Accomodation (Function)</td>
<td>6.10.1.1  EMT (Requirement)</td>
</tr>
<tr>
<td>6.10.1  Body Accommodations (Requirement)</td>
<td>6.10  Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td><strong>SS.10.2 Cab/Patient Compartment Access Window (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.10.2.1  Compartment Access Window (Fabrication) (Function)</td>
<td>6.10.2.1  Fabrication (Requirement)</td>
</tr>
<tr>
<td>6.10.2  Cab/Patient Compartment Access Window (Requirement)</td>
<td>6.10  Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td>Allocated Capabilities/Requirements</td>
<td>Traced From Higher-Level Elements</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>SS.10.3  EMT Seating (Component)</td>
<td></td>
</tr>
<tr>
<td>SS.10.3.1  EMT Seating Dimensions (Function)</td>
<td>6.10.3.1  Dimensions (EMT) (Requirement)</td>
</tr>
<tr>
<td>SS.10.3.2  EMT Seating Placement (Function)</td>
<td>6.10.3.2  Placement (EMT) (Requirement)</td>
</tr>
<tr>
<td>SS.10.3.3  EMT Seating Furnishing (Function)</td>
<td>6.10.3.3  Furnishing (EMT) (Requirement)</td>
</tr>
<tr>
<td>SS.10.3.4  Infant Safety Seat (Function)</td>
<td>6.10.3.4  Infant Safety Seat (Requirement)</td>
</tr>
<tr>
<td>6.10.3  Emergency Medical Technician (EMT) Seating (Requirement)</td>
<td>6.10  Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td>SS.10.4  Patient Compartment Interior Dimensional Parameters (Component)</td>
<td></td>
</tr>
<tr>
<td>SS.10.4.1  Length (Function)</td>
<td>6.10.4.1  Length: (Requirement)</td>
</tr>
<tr>
<td>SS.10.4.2  Width (Function)</td>
<td>6.10.4.2  Width: (Requirement)</td>
</tr>
<tr>
<td>SS.10.4.3  Height (Function)</td>
<td>6.10.4.3  Height: (Requirement)</td>
</tr>
<tr>
<td>6.10.4  Patient Compartment Interior Dimensional Parameters (Requirement)</td>
<td>6.10  Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td>SS.10.5  Body Construction (Component)</td>
<td></td>
</tr>
<tr>
<td>SS.10.5.1  Modular Construction (Function)</td>
<td>6.10.5.1  Modular Construction (Requirement)</td>
</tr>
<tr>
<td>SS.10.5.1.1  Finishing (Function)</td>
<td>6.10.5.1.1  Finishing (Requirement)</td>
</tr>
<tr>
<td>SS.10.5.1.2  Design (Ambulance Body) (Function)</td>
<td>6.10.5.1.2  Design (Ambulance Body) (Requirement)</td>
</tr>
<tr>
<td>SS.10.5.1.3  Material (Function)</td>
<td>6.10.5.1.3  Material (Ambulance Body) (Requirement)</td>
</tr>
<tr>
<td>SS.10.5.1.4  Load Test (Function)</td>
<td>6.10.5.1.4  Load Test (Ambulance Body) (Requirement)</td>
</tr>
<tr>
<td>SS.10.5.2  Roof Structure (Design and Construction) (Function)</td>
<td>6.10.5.2  Roof Structure - Design &amp; Construction (Requirement)</td>
</tr>
<tr>
<td>6.10.5  Body, General Construction: (Requirement)</td>
<td>6.10  Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td>SS.10.6  Body Structure (Component)</td>
<td></td>
</tr>
<tr>
<td>SS.10.6.1  Body Structure (Function)</td>
<td>6.10.6.1  Body Structure (Requirement)</td>
</tr>
<tr>
<td>SS.10.6.1.1  Fasteners (Function)</td>
<td>6.10.6.1.1  Fasteners (Requirement)</td>
</tr>
<tr>
<td>SS.10.6.1.2  Assembly Materials (Function)</td>
<td>6.10.6.1.2  Assembly Materials (Requirement)</td>
</tr>
<tr>
<td>Allocated Capabilities/Requirements</td>
<td>Traced From Higher-Level Elements</td>
</tr>
<tr>
<td>-----------------------------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>SS.10.6.1.3 Roof Panel (Function)</td>
<td>6.10.6.1.3 Roof Panel (Requirement)</td>
</tr>
<tr>
<td>SS.10.6.1.4 Extended Roof (Function)</td>
<td>6.10.6.1.4 Extended Roof (Requirement)</td>
</tr>
<tr>
<td>SS.10.6.1.5 Gussetting (Function)</td>
<td>6.10.6.1.5 Gussetting (Requirement)</td>
</tr>
<tr>
<td>SS.10.6.1.6 Drip Rail (Function)</td>
<td>6.10.6.1.6 Drip Rail (Requirement)</td>
</tr>
<tr>
<td>SS.10.6.2 Body Skirt, Roof and Panel Joints (Function)</td>
<td>6.10.6.2 Body skirt, and Body, Roof and Panel Joints (Requirement)</td>
</tr>
<tr>
<td>6.10.6 Ambulance Body Structure: (Requirement)</td>
<td>6.10 Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td><strong>SS.10.8 Doors (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.10.8.1 Side Opening (Function)</td>
<td>6.10.8.1 Side Opening (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.1.1 Dimensions (Side Door) (Function)</td>
<td>6.10.8.1.1 SO Dimensions (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.2 Rear Door (Function)</td>
<td>6.10.8.2 Rear Door (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.2.1 Dimensions (Rear Door) (Function)</td>
<td>6.10.8.2.1 RO Dimensions (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.3 Materials (Function)</td>
<td>6.10.8.3 Materials (Doors) (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.4 Release (Function)</td>
<td>6.10.8.4 Release (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.5 Leakage (Function)</td>
<td>6.10.8.5 Leakage (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.6 Inner Panel (Function)</td>
<td>6.10.8.6 Inner Panel (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.7 Reflector (Function)</td>
<td>6.10.8.7 Reflector (Requirement)</td>
</tr>
<tr>
<td>SS.10.8.8 Protection of Patients and Crew (Function)</td>
<td>6.10.8.8 Protection of Patients and Crew (Requirement)</td>
</tr>
<tr>
<td>6.10.8 Doors (Requirement)</td>
<td>6.10 Ambulance Body and Patient Area: (Requirement)</td>
</tr>
<tr>
<td><strong>SS.10.10 Floor (Component)</strong></td>
<td></td>
</tr>
<tr>
<td>SS.10.10.1 Design and Construction (Function)</td>
<td>6.10.10.1 Design &amp; Construction (Floor) (Requirement)</td>
</tr>
<tr>
<td>SS.10.10.2 Voids or Pockets (Function)</td>
<td>6.10.10.2 Voids or pockets (Requirement)</td>
</tr>
<tr>
<td>6.10.10 Floor: (Requirement)</td>
<td>6.10 Ambulance Body and Patient Area: (Requirement)</td>
</tr>
</tbody>
</table>
APPENDIX E - FIGURES

E1  1400 lb body load, additional and adjusted columns, 0.792 and 0.875 inches

Figure 43. Deformation on an adjusted bio-mimicked frame with 0.792 and 0.875 radii of body load, 1400 lb (x)

Figure 44. Direct stress on an adjusted bio-mimicked frame with 0.792 and 0.875 inches radii of body load, 1400 lb (x)
Figure 45. Maximum combined stress on an adjusted bio-mimicked frame with 0.792 and 0.875 inches radii of body load, 1400 lb (x)

Figure 46. Minimum combined stress on an adjusted bio-mimicked frame with 0.792 and 0.875 inches radii of body load, 1400 lb (x)