Auto Balancing Ambulance Stretcher with Active Control to Mitigate the Discomfort of the Patient

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Abstract— During a medical emergency, the time taken to transport a critically ill or injured patient to the closest medical centre is a key factor determining the life and death of the patient. Although the current ambulances have attained the capability of passenger transport at a higher rate, the inability of the same designs to cater to the level of comfort during this journey has led to an increase in the mortality rates. The solutions for the above problem are either to build an ambulance, or to improve the design aspects of the stretcher, in order to ensure the required level of comfort to the critical patient. This study suggests a stretcher design capable of three degrees of freedom, which is used to counteract the discomfort caused by centrifugal accelerations and vibrations. The tests conducted have proven the capability of the stretcher to reduce the vibrational effect experienced by the subject by 58%, while bringing the maximum vibration well below 2Hz, the effect due to inertial accelerations by 92%, and effect due to centrifugal acceleration by 88%. Considering the ergonomic characteristics and lower cost associated, the suggested design shows feasibility of using the apparatus in developing countries like Sri Lanka.

***Keywords**: auto-balancing ambulance stretcher, mitigate discomfort, inertial forces, 3-DOF*

I. INTRODUCTION

In medical emergencies, the ambulances are used as the main mode of transport of patients from the scene of the incident to the hospital or from one hospitals to another. In order to save lives of patients who are transferred from ambulanaces, time taken for the task must be shortened as much as possible. While treating this aspect as the main factor, safety and comfortability of the patient during the journey to the hospital are also considered as other critical factors that affect the life of the patient. However, when rushing patients to the hospitals becomes the priority, both safety and comfort of patients during the journey are often compromised. In the current ambulance designs and the patient supporting set up inside ambulances, there are ineffective devices are available which fail to reduce the discomfort of patients inside a fast moving ambulance. Hence, this study aimed to develop an auto balancing ambulance stretcher to mitigate the discomfort of the patients inside a ambulance during the visit to the hospital.

II. LITERATURE REVIEW

Illnesses and injuries are unpredictable and could cause at any place or any time. For such instances, ambulances are placed under the broad umbrella of Emergency Medical Services commonly known as EMS (T.ZobelJ, 2004). Ambulance development has come a long way since the first encounter of carrying a patient in 1497, where the patient was carried on carts using horses (Bell, 2009). In the latter part of the 19th century, the development of motorized systems induced the use of motor vehicles as ambulances. The structure of ambulance was laid down during the world war period, incorporating a physician and medical equipment, which is mandetory inside the ambulance since it resulted in a significant reduction in mortality rate during travel (Bell, 2009). Lieutenant Clifford Peel came up with a fixed wing aircraft design named as ‘Air Ambulances’ in 1917 (King, 2004). With the evolution in technology, modern day ambulances have four major categories (Gainor, 2015). They are classified as Type I, Type II, Type III and Type IV. Type I ambulance is used in scenarios such as advanced life support and mobile intensive care. Type II ambulances are used for basic life support. Type III has a custom built van chassis and a rear compartment. Type IV is built under international standards, but have the capability to travel through restricted areas (HAMPSON, 2007). CEN1789 is the regulation published by the European Committee for standardization for the compliance level required to be adhered for

Ambulances. United States follows KKK-A-1822F which is published by the General Services. NFPA 1917 issued by the National Fire Protection Association is a globally recognized report, suggesting the design standards for ambulances. These were further influenced by the national ambulance standards for countries like Sri Lanka and India. It is noted that reduction in the patient compartment area while keeping minimum height of the patient compartment is due to the presence of only type II ambulances for emergency medical services (COUNCIL, 2013). Most of the current developments in the ambulance design had been unable to address the effects to the patient during travel. These include inertial forces caused by acceleration and deceleration, centrifugal forces due to ambulances taking bends at higher speeds and by vibration generated due to the roadside deformations and those transmitted from the mechanical components of the ambulance. According to the study (Waddel, 1975), the mortality rate of patients who suffered from hypertension is around 67%, hypotension is 50%, and delayed hypotension is around 29% (G.Waddel, 1975). Wheble (1987) further stated that, patients who arrive at the hospitals experience worse medical conditions than that prevailed before they were transported. Snook (1972) stated that the health condition of the patient can be directly and indirectly affected by the movement of the vehicle. The body sway causes physical and psychological effects, which may cause a rise or fall of blood pressure, critical heart arrest and cardiac arrythmia (Snook, 1972). As the main factor to be mitigated during travelling, the body sway caused by inertia, centrifugal forces and vibrations play a major role in minimalizing the mortality rates of patients. According to Ono, these external forces cause variation in blood pressure and body sway (Ono & Inooka, 2009). Pre-surgery hypertension plays a critical factor in determining the outcome of any surgery. Around 75% of the patients transported through ambulances undergo surgery procedures, thereby if a patient is to be affected by blood pressure variations in the pre-surgery stage, he/she will face serious consequences. Several notable designs had been developed with the aim of mitigating the effect on a patient due to vibration, centrifugal forces caused due to ambulances taking bends at higher speeds, inertial forces caused due to instant acceleration and deceleration (Abd-El-Tawwab, 2001). Ono and Inooka (2009) have proposed an active-controlled bed for the ambulances as shown in Figure 1.

Figure 1. Active Control Bed (Ono & Inooka, 2009)

According to them the discomfort caused due to the inertial acceleration and deceleration degrades the medical condition of the patients. The ACB is designed to be able to move in two axes of rotations. These two rotations will permit the cancellation of the longitudinal and lateral acceleration of the patient.

A special air suspension system was installed in this system so that the vibration and shocks induced by the road are absorbed. To reduce the impact of engine vibration and shocks, a low pass filter was added to the data acquisition model thereby these noises do not affect the readings taken by the system. In the implementation of the proposed design, several constraints were added to the system to prevent any discomfort to the patient. The constraints were added in order to prevent bed's motions inversely affecting on the subject.

The Active-Controlled bed suggested by Ono and Inooka (2009) does not meet the International standards for stretcher dimensions. Additionally, hard braking leads to nose driving which causes a rebound motion of the stetcher which is uncomfortable to the patient.

The prime goal of present work is to devise a mechanism to mitigate the impact on patients travelling on an ambulance stretcher due to inertial, centrifugal accelerations and vibrations. The research focusses upon the 3 degrees of freedom, where platform is considered as the main mechanism which is to be used to provide the desired motion for the ambulance stretcher. Three Degrees of freedom platforms belongs to the sector of parallel robots (Staicu, 2005). The limbs are composed of prismatic actuators giving the capability to the 3 DOF platform to increase and decrease the length between the two platforms. Generally, the joints used in the mechanism are revolute joints and ball joints. The presence of 3 revolute joints provides the capability to the platform to tilt in 3 degrees of freedom namely Roll, pitch and rotation around the z-axis.

III. METHODOLOGY

This research mainly focuses on mitigating the forces acted upon the patient throughout the journey in the ambulance. An initial study in this regard revealed that, only the suspension system supports to mitigate the discomfort caused during travel. Majority of ambulance stretchers are firmly attached to the chassis of the vehicle, thereby subjected to the movements of the ambulance, upon the patient. These movements that act upon the patient causes physical and psychological changes which could lead to mortality, and thereby causing substantial impact on mortality rates of critical patients, during transport. Methodology of the study is show in Figure 2.

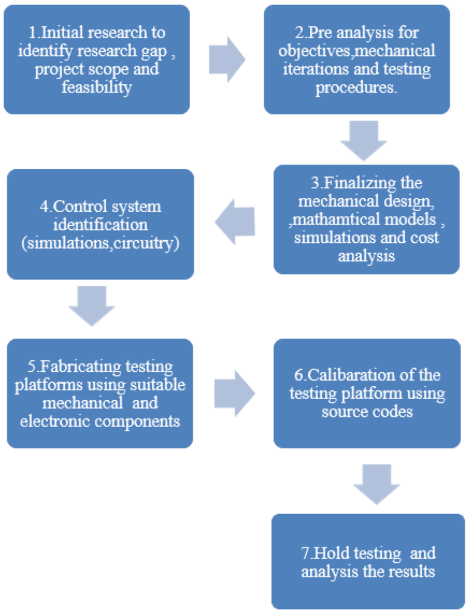


Figure 2. Flow Diagram showing the methodology

From the literature review, publications related to the effects of ambulance on critically ill patients (Waddel, 1975) and actively-controlled beds for ambulance (Ono, 2009) were studied further to lay the foundation for the proposed design. However, in this study, 6 main directions of movement which are left, right, upwards, downwards, slope up and slope down were considered. Mechanical simulations were conducted initially. Here, the iterations were done for the active control bed model developed by Ono and Inooka (2009). Analysis was conducted using the statistical analysis model suggested by Ono and Inooka (2009).

IV. DESIGN AND FABRICATION

A. *Mathematical Model*

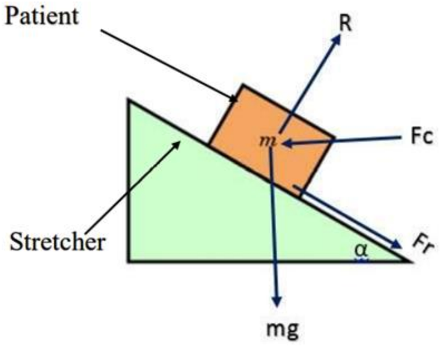


Figure 3. Free body diagram

The tilt of the stretcher is one of the key factors determining the level of comfort experienced by the patient. Figure 3 shows the free body diagram of the forces exerted on the patient's body, when the upper platform is turned by an angle of α.

The terminology used in the calculation are as follow:

R- Normal reaction on the patient's body from the stretcher
F_c- Centrifugal force acting upon the patient
F_r- Frictional Force acting on the patient
m- Mass of the patient
g- Acceleration due to gravity
µ- Coefficient of friction
θ_d- Desired tilt angle

The equilibrium condition was taken into consideration by applying Newton's second law along and in perpendicular directions. Considering the equilibrium in the direction perpendicular to the plane (Direction of R),

$$R - mg.\cos\alpha + F_c.\sin\alpha = 0 \text{ ------- } (1)$$

Considering the equilibrium in the direction along the plane (Direction of F_r),

$$F_r = F_c.\cos\alpha - mg.\sin\alpha \text{ ---------- } (2)$$

By equating these equations, the following kinetic model was obtained (Here $\theta_{d} = \alpha$) .

$$Desired\ platform\ tilt = \theta_d = \tan^{-1}\left[\frac{(F_c - \mu mg)}{(mg - \mu F_c)}\right] \quad G. \text{ ----- } (3)$$

Free body diagram shown in Figure 4 represents forces exerted on the patient's body when the upper platform is turned by an angle of θ when subjected to linear acceleration.

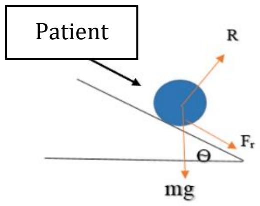


Figure 4. Freebody Diagram of patient on stretcher

By applying F=ma perpendicular and horizontal to the stretcher:

$$\theta = \frac{1}{2}Sin^{-1}\left(\frac{\alpha-\frac{\mu g}{2}}{\frac{g}{2}\sqrt{1+\mu^2}}\right) - \frac{1}{2}Sin^{-1}\left(\frac{\mu}{\sqrt{1+\mu^2}}\right) \quad \text{--- (4)}$$

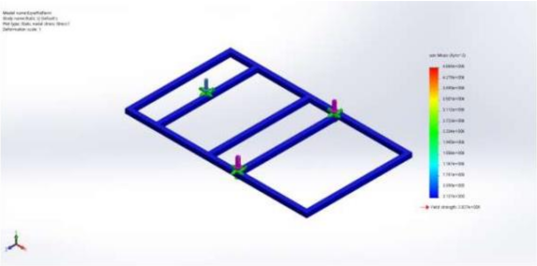
Equation 4 gives, the required angle of tilt during an event of linear acceleration:

Additionally, for the mechanical design, the required torque for the motors were calculated as 1.718 Nm. Required motor speed was calculated as 1875 rpm. The natural frequency of the system was calculated as 8.1 Hz. The required minimum spring constant for 2 Hz was obtained as 2962.59 Nm^{-1}.

B. *Mechanical Design*

Stewart platform, which is one of the main prismatic actuators, feedback control system with a gyroscopic sensor and accelerometer were the main mechanisms in this study. Final design was established from the conceptual design, simulation results and, structural analysis of the design conducted using SolidWorks2018. The functions of the design, specifications of the components and the mechanical structure of the design were given as inputs. Figure 5 gives the stress analysis of the design.

I. Figure 5. Stress Analysis



Name	Type	Min	Max
Stress1	VON: von Mises Stress	3.137e+000N/m^2 Node: 471	4.668e+006N/m^2 Node: 16883

Properties such as material density, low brittleness, high tensile and compressive strength, cost effectiveness, desirable ductililty and malleability were considered. It was decided that the most suitable metal for this design is low carbon steel. Railing mechanism, guiding device and locking mechanism were the most critical points of the mechanical design. Ball bearing slider, vertical and horizontal guides and auto lock while inserting mechanisms have been used since the process of entering patient into the ambulance should be an urgent matter. According to the analysis, a customized linear actuator was obtained to satisfy the needful. This actuator has a stroke of 300 mm, 24V DC output, maximum load of 250 N and a speed of 45 mms^{-1}. Additionally, dampers which suited the requirement were selected.

C. *Control System Design*

Gyroscopic and accelerometer readings were taken as main inputs. Developing an algorithm for prismatic actuation and elevation which has 3 linear actuators based on the gyroscopic and accelerometer reading was the main part of the coding. Here, the feedback of the system is the encoder reading of the motor.

D. *Wiring connections*

Circuitry was developed using two microprocessors which are RaspberryPi B3+ and Arduino Mega 2560. Additionally, two accelerometers (MPU 6050) were used to obtain analog readings of orientation and acceleration on the stretcher and the ambulance separately. Further, RaspberryPi 3B+ was used in the HMI system. Arduino Mega 2560 was used in the electrical system due to the high-speed data transfer rate of MPU 6050. Accordingly, the device was programmed using Python and Arduino for the required operations. The, gyroscopic and the accelerometer readings were taken as the inputs for the system. A propotional movement was developed from the coding system. Executing proper "if" conditions to the gyroscopic readings, the tilt angle was calculated and the feedback was added to the calculation, thereby, enhancing the motion of the ambulance bed. The HMI was coded afterwards while debugging the system and conducting the necessary tests. A Kalman filter was used as the elevation angle reading library to enhance the reading values of the MPU6050. Figure 6 shows the final fabricated design of the active control bed.

Figure 6. Final Fabricated Design of the Active Control Bed

V. TESTING AND RESULTS

Analysis was conducted using the statistical analysis model suggested by Ono and Inooka (2009). For this, the subject selected for the tests was a dummy that weighed 50 kg. Type II ambulance was used for the test and the airport road in-front of the Ratmalana airport was selected as the location to conduct the test. Accordingly, the following tests were conducted.

Test 1: Evaluating the design dimensions

When evaluation the design dimensions, the limitations provided by the International Standards NFPA 1917 and the Guideline for Government and Private Ambulance Services of Sri Lanka were taken into consideration. The minimum distance of the walkway between the ambulance stretcher and the paramedic sheet is 300 mm. The minimum distance from rear doors to the rear edge of the ambulance stretcher is to be 254 mm. Additionally, maximum allowable height of the stretcher in the loading position is to be 700 mm. After the design was attached to the ambulance body, the required measurements were taken as follows. Minimum distance of the paramedic walkway was 320 mm. This is a 6.67% positive variation from the required value. Minimum distance from the door to the stretcher was 340 mm. This is a 33.86% positive variation. Also, the maximum allowable height during operation was measured as 720 mm. This is a 2.86% positive variation from the required value.

Test 2: Evaluating the performance of dampers

For this test, two gyroscopes of model ICM42605M were used. Here, the application developed by RWTH Aachen University, Phyphox was used in order to gather data. One accelerometer was set to the developed device and the other was attached to the stretcher frame. The difference in the readings taken from the stretcher and the stretcher frame was considered as the evaluation here. The tests were mainly conducted for 2 different speeds, 50 kmph^{-1} and 75 kmph-1. The speed was maintained for 15 seconds and the data was gathered. For the purpose of comparison, the results obtained from 75 kmph^{-1} was considered. According to the results obtained, with respective to the conventional stretcher, the active control bed was able to obtain 58% reduction in vibration throughout the session at 75 kmph^{-1}.

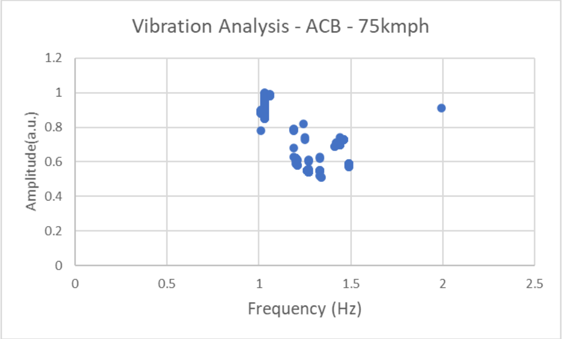


Figure 7. Vibration Analysis of Active Control Bed at 75 kmph

Test 3: Evaluating the stretcher response for the instant acceleration

According to the mathematical model and the constraints set by the dimensions of the design, the maximum tilt that the device should allow is 20 degrees. Here, the data retrieved from MPU6050 and the acceleration data gathered form the phyphox application using ICM42605M were compared. The ambulance was tested against an acceleration until it reached a speed of 75 kmph^{-1}. Ambulance took 20 seconds to reach the targetted speed. Within this time, the acceleration achieved and the tilt obtained were recorded separately. From the acceleration, the required tilt was calculated, and the required tilt was compared with the achieved tilt.

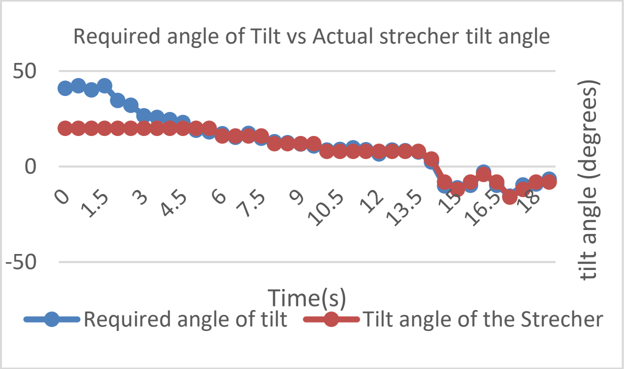


Figure 8. Required Tilt Angle vs Actual Tilt Angle on Instant Acceleration

The required tilt of more than 20 degrees was considered as the uncontrollable region. A deviation of 66.8% from the required tilt was observed. However, in the controllable region, only a deviation of 2.17% was observed. Within this range, the stretcher performed with a maximum error of 2 degrees. Therefore, it was calculated that the stretcher responds with an accuracy of 92% of the recorded inertial acceleration.

Test 4: Evaluating the stretcher response against instant deceleration
Here, the test was similar to Test 3, but the ambulance was brought to a halt from a speed of 75 kmph and the data was recorded. Similar to Test 3, the required tilt angle of the recorded de-acceleration was calculated and compared with the achieved tilt. Here a percentage variation of 23.1% was observed between the required and the achieved tilt. The calculated ambulance stretcher response efficiency was 77%. It should be noted that here the stretcher was restricted to nose driving. Hence a reduction was expected in the efficiency. Maximum deviation of tilt was recorded as 3 degrees for this session.

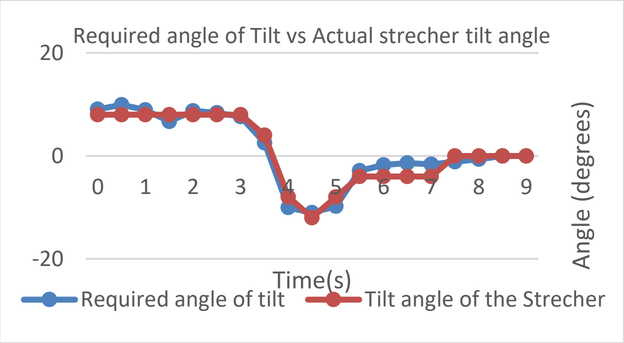


Figure 9. Required Tilt Angle vs Actual Tilt Angle on Instant Deceleration

Test 5: Evaluating the stretcher response against centrifugal acceleration
For this test, the ambulance was tested against a bend acquiring 50 kmph^{-1} and 75 kmph^{-1}. Here, the data was recorded for 12 seconds and from the acceleration data gathered, the required tilt of the stretcher was obtained. Shown below is the tilt comparison for 75 kmph^{-1}.

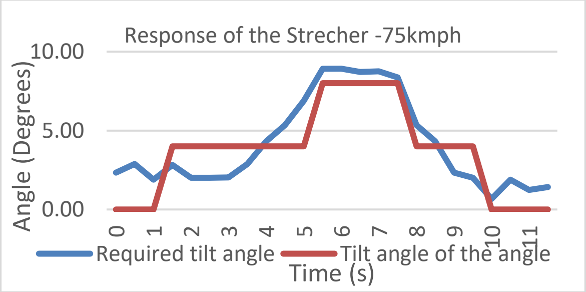


Figure 10. Required Tilt Angle vs Actual Tilt Angle on Centrifugal Forces

The responsiveness for accelerations above 1 ms^{-2} stands at 88% at 75 kmph. It showed a responsiveness of 82% for 50 kmph indicating that the bed is more responsive for higher changes in acceleration.

VI. DISCUSSION

The objective of this research is to design, fabricate and evaluate the performance of an autobalancing ambulance bed with the capabaility of absorbing intertial and centrifugal forces upon the patients. In this study, steward platform has been utilized as the basis for mechanical design. The final fabricated apparatus was able to exhibit 3-DOF which is essential in counteracting the interial and centrifugal forces. In the performance evaluation phase of the apparatus, 5 tests were conducted.

Design ergonomics of the fabricated design has shown a variation of 6.67% related to the distance from the paramedic walkway. All the other ergonomic factors attributed were within the threshold.

Tests were conducted in order to verify the functional aspects predetermined against the international standards published on the comfort and safety of patients travelling in ambulances. The statistical analysis model suggested by Takahiko and Inooka (2009) was used in this regard. From the test results, it was found that the active control bed designed was complied with the limitations provided by the International Sandards NFPA of 1917 and the Guideline for Government and Private Ambulance Services of Sri Lanka. The designed active control bed showed a 58% reduction in vibration compared to the conventional stretcher used in the ambulance. The bed was able to operate under 92% accuracy for the responsiveness against instant acceleration. When the ambulance was taken into halt with an instant deacceleration, the bed was able to operate under an efficiency of 77% accuracy. The action against centrifugal accelerations provided a responsiveness of 88% by the active control bed, thereby it was able to improve the patient comfort and to mitigate the discomfort compared to that of the conventional stretcher.

VII. CONCLUSION

It can be concluded that the stretcher is capable of absorbing majority of inertial forces acting on human body when the ambulance is driven at 75 kmph. The overall cost of the apparatus shows that auto balancing strecher proposed in this study can be locally manufactured at a cost similar to NF A9 emergency stretcher (Without the auto balancing capability), making it a feasible remedy for the fatalities and discomfort caused due to the inertial, vibrational and centrifugal accelerations.

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