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Design and Evaluation of Wearable Exoskeleton to Augment Load Carrying Capacity for Ground Force Soldiers

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Abstract:
This paper presents the first part of mechanical design phase in designing and evaluating a wearable lower limb exoskeleton suit, the device is intended to be used for soldiers to augment a load carrying capacity during long distance walking with heavy loads in military missions. Currently the technological developments in military combats mainly focus on designing devices as an added weight of personal belongings to be carried by soldiers for personal safety and mission accomplishment, but this technological development has not given more focus in supporting mechanism with respect to the added weight to individual soldiers, although in most countries military group including the present study group of this paper, the recommended weight is considered as (23-25) Kg, this limit has not been kept as a rule from biomechanics point of view due to the above reason. In this paper a new design is included in exoskeleton that supports a load based on gravity compensating mechanism at the hip joint and reduces the torque at the knee joint, this device develops a compensating torque due to the stored energy in the torsion spring mechanism. Preliminary design synthesis and product design process has been implemented using digital human modeling software considering comfort of the users and adjustability of the device for various populations. Finite element analysis is conducted in addition to analytical results that will help in deciding the structure. In the result section four data of masses (25Kg, 30Kg, 35Kg and 40Kg) are used for evaluating newly designed load compensating mechanism with four height variations, thus to arrive at an appropriate knee joint torque requirements which will help in selecting an effective actuator. Finally a comparison has been made for the actual torque required at knee joint, firstly without considering the effect of gravity compensating torque an average result was found as 248.32 Nm and by considering the effect of gravity compensating torque it is found to be 174.4 Nm which is 29.8% decrease due to gravity compensating system, the rest of the load will be transferred through the main links. Hence this result shows an improved design that helps for future research direction.

Keywords: Exoskeleton, Finite Element Analysis, Gravity compensation, Torsion spring.

I. INTRODUCTION

The primary objective of this paper is to design the wearable lower extremity that can be used to augment soldier's strength and endurance during specific military mission that requires traveling a long distance with unfavorable road and considerable heavy loads or personal belongings. Load carriage is defined here as a movement while transporting an external mass supported on the upper torso by shoulder straps and/or hip belts. This load that can be carried using the backpacks in most countries military personnel including the military populations focused in this paper is approximated as (23-25) Kg, But the current practical weight is above this limit, because of the recent technological developments in the field of army science, various additional equipment's such as night vision goggles, GPS (global positioning system) units, body armor and extra bullets are few of the loads that has a contribution for increased weight.

The increase of this heavy equipment's are considered as the soldiers desire to be sufficiently equipped to ensure personal safety in any circumstances as well as to take advantages of the fighting power against enemies [1]. In this paper main task is focused on kinematic modeling and designing the exoskeleton with a unique backpack support which is aimed to help mobility and load carrying capacity of special forces in harsh areas where other means like wheeled transportations are not possible, for this purpose many wearable lower extremity power augmenting exoskeletons have been proposed focusing on relieving the weight of the backpacks [2-6]. However as proposed in some other researches these types of exoskeleton tend to hinder the natural gaits of wearers owing to the excessive application of actuators for all joints as well as kinematic problems[7].

In this study it has been given an insight to analyze various design requirements through existing research for proposing a wearable exoskeleton with special load supporting mechanism which do not hinder the usual activities of soldiers during mission accomplishments such as walking a sloppy road with loads that eliminates unnecessary forward flexion of the torso that leads to back pain.

II. EXOSKELETON DESIGN OVERVIEW

Anthropomorphic Architecture

It is a method of kinematically matching the two joints, by kinematically matching the human degrees of freedom and limb lengths with the exoskeleton, it is possible to make the exoskeletons leg position to exactly follow the human legs position. The above method simplifies several design issues such as human/exoskeleton collisions, similarly in this architecture the exoskeleton limb lengths are made same with the user so that adjustability is taken into consideration for different users.in this paper anthropomorphic architecture is selected because of its kinematics and ergonomically fitted to the infantry soldiers for specific missions.

Non anthropomorphic Architecture

Non anthropomorphic architectures it is a method of kinematically matching only few joints of the users to the exoskeleton but due to kinematic mismatching to some joint a considerable collision will occur between the user and exoskeleton, hence it is not common in exoskeleton design.

Mechanical effects of Back pack type and load distribution

In most of the previous studies it is shown that while the duration of the stance phase of gait (foot on the ground) is not affected by loads of up to 50% of body weight, the duration of the swing phase (foot in the air) decreases with increased load. The result is an increase in the percentage of double support (both feet on the ground at the same time) with load [8].As the load increases, force exerted by the feet on the ground increases in the downward, forward, and rearward [9-12]. Regarding type of packs which is intended to take the loads totally or partially to the ground are explored in some studies [13] used a pack with a well-designed hip belt that distributed a large portion of the load to the large muscles of the legs.

The pack used by [14] did not have a belt of this type and placed a larger portion of the load on the smaller muscle groups of the upper body. This may have resulted in more rapid fatigue of some upper body muscle fibers which results in subsequent recruitment of additional muscle groups, and thus an increase in energy expenditure

Load Placement Techniques

The location of the load in the pack is known to affect energy cost of walking and influence body mechanics, in some study it shows higher energy cost were related with a load that was lower in the pack and farther away from the body than the reverse [15].

Both high and low load placement results in forward body leaning and its greater for lower load placement because the lower load requires more forward body rotation about the hips or ankles to bring the pack center of mass over the feet. Mid-back rather than high-back load placement has been recommended as a means of reducing torso muscle tension during load carriage, particularly during unexpected stumbles where high-load placement can necessitate relatively high muscle forces to maintain postural stability.

Biomechanics of Human Motion

Human's movement and motion are very complex due to the vast number of degree of freedom of our body. However, most of our daily life motions that require large torque and power are performed in the sagittal plane [16].

These motions include walking, running, standing up and more. This is the reason why many of the previous studies focused on actuation of joint in sagittal plane particularly in flexion/extension of hip, knee and ankle as seen in [17].Figure-2 depicts an uphill movement where the force generated by the body weight and backpack load produces an internal moment M_{int} which opposes the opposite leg to step forward hence an external moment M_{ext} due to knee torque and an additional actuator must counteract this M_{int} in order to be in standing posture with the load.

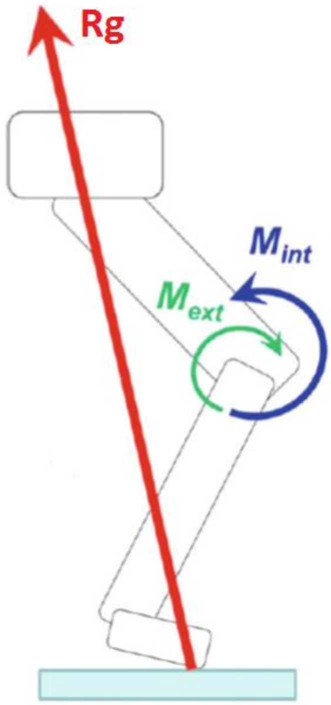


Figure.1. Kinematic of load carrying in biomechanics

III. PROBLEM STATEMENT

The current design in this paper is aimed at an assistive device that increases the performance of soldiers and reduces the non-combat related injuries which occurs due to additional loads carried at the backpack while traveling long distance in unstructured road. Hence an under actuated exoskeleton for lower extremity is proposed, that has a unique feature of gravity load compensating mechanism using a weight compensating spring system at the hip joints and actuators at the knee joints.

IV. CONCEPT DEVELOPMENT

The most important phases in product design and development process is to arrive at the final best concept after passing various rigorous screening criteria, this criteria starts from a design sketch up to product ranking process. The final concept is selected as one which has a load compensating system at the hip joints that can transmit the backpack loads directly to the ground by the principle of gravity weight compensation. Consideration has been made in the product to be ergonomically comfortable that can embrace the pelvic as well as other body interfacing parts with appropriate cushion between exoskeleton and human interface, because of the movement of this system, it plays a great role by dynamically adjusting a gravity compensating mechanism to enable free and balanced movement of the soldiers in different terrains. The proposed mechanism in figure-2, shows the torsion spring joins the c-frame with lower link which acts as flexible joint in compensating backpack load by restoring spring energy during forward walking. Figure-3 shows the mechanism with appropriately selected anthropometric data (50 percentile, 75 Kg soldier model) in digital human modeling environment using Catia v6 and rendered. It is considered as a bipedal wearable robot with 3 degree of freedom at each limb which allows the hip, knee and ankle joint to be rotated in the Sagittal plane. Aluminium-7075 which is light and at the same time strong is selected as a material for the exoskeleton links thus a total weight of the new exoskeleton is 4.5 kg or 2.25kg at each sagittal side of the wearer.

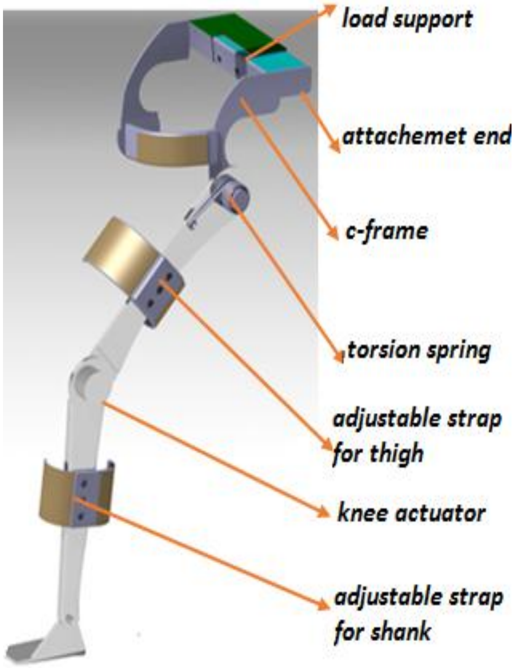


Figure.2. Rendered CAD model of the developed Concept (Left lower limb Exoskeleton).

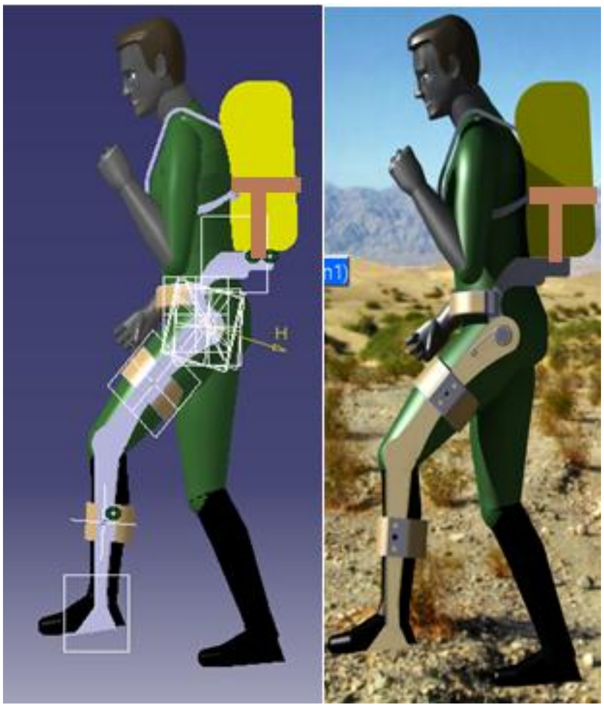


Figure.3. Digital human model with the developed concept (Left) after rendering in desert background (Right)

V.KINEMATIC ANALYSIS

In order to control the lower limb exoskeleton, the relationship between joint angles and position of the foot must be identified, considering an anthropomorphic or commonly designated as Rotational-Rotational-Rotational (RRR) series planar robot due to its movement only on Sagittal plane and having three joints. Forward kinematics is applied to find the position of the foot by considering the values for the joint angles are given. First, reference frame are assigned to the hip, knee and ankle joint as shown in Figure-4. By using the reference frame assigned, the Denavit-Hartenberg (DH-parameter) table that represents the translational and rotational relationship between links is constructed for one side of the leg as depicts in Table-1. Where i=1, 2.3.

Table.1. D-H Parameters

Exo-Links	Joint	αi-1	ai-1	di	ϕi
Hip	1	0	0	0	ϕ1
Knee	2	0	L1	0	ϕ2
Ankle	3	0	L2	0	ϕ3

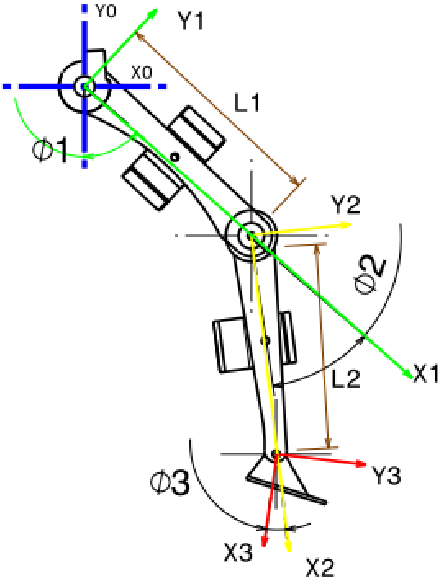


Figure.4. (3-Degree of Freedom Kinematic Model of Left Leg Exoskeleton)

Applying a 4 x 4 homogeneous transformation of link i with respect to link i-1, the poison of the end effector or foot relative to the hip and knee joints can be obtained from the position vector of equation-3 and shown in equation-4 and equation-5, the overall sequence of derivation for joint i is given in equation-2and it can also be configured as equation-1.To control the position by left or right actuators at the knee due to reference coordinates the transformation matrix is given as in equation-1,Sϕ12=(sin(ϕ1+ϕ2) and Cϕ12=cos(ϕ1+ϕ2) respectively)

$$ {}^{0}_{2}T = {}^{0}_{1}[T]\,{}^{1}_{2}[T] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (1) $$

$$ {}^{i-1}_{\ i}T = \begin{bmatrix} C\phi i & -S\phi iC\alpha i & S\phi iS\alpha i & aiC\phi i \\ S\phi i & C\phi iC\alpha i & -C\phi iS\alpha i & aiS\phi i \\ 0 & S\alpha i & C\alpha i & di \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ..(2) $$

$$ {}^{0}_{3}T = \begin{bmatrix} C\phi 123 & -S\phi 123 & 0 & L1C\phi 1 + L2C\phi 12 \\ S\phi 123 & C\phi 123 & 0 & L1S\phi 1 + L2S\phi 12 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots\ (3) $$

$$ X = L1C\phi 1 + L2C\phi 12 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4) $$

$$ Y = L1S\phi 1 + L2S\phi 12 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5) $$

The inverse kinematics for determining the joint angular positions are given as shown in equation-(6) and (7).

$$\phi 2 = \pm \frac{\sqrt{(2L1^2 + L2^2) - [X^2 + Y^2 (L1^2 + L2^2)^2]}}{X^2 + Y^2 - (L1^2 + L2^2)} \text{ ..(6)}$$

$$\phi 1 = \tan^{-1}\left(\frac{X}{Y}\right) - \tan^{-1}\left(\frac{L2S\phi 2}{L1 + L2C\phi 2}\right) \text{ …………..... (7)}$$

VI. JOINT TORQUE ANALYSIS

The maximum joint torque while moving with heavy loads are considered to act at the knee joint hence in this paper more concentration is given in determining this torque or restoring moment due to weight of the user and load carried at the back. The worst scenario of moving posture is taken for analysis as shown below in figure-5, As the next stance starts by the opposite leg the strain energy stored in the torsion spring tends to gravity - compensate the pack load by moving it up ward hence the entire cycle of mobility can be smoothly achieved.

Note in this paper SI units are adopted throughout the calculation , the anthropometric data is taken for average soldier of 75Kg weight and a stature of soldiers considered in this paper is >1.5m which is 1.7m,similarly standard military load carrying pack size of (450×280×220) mm is taken for the design.

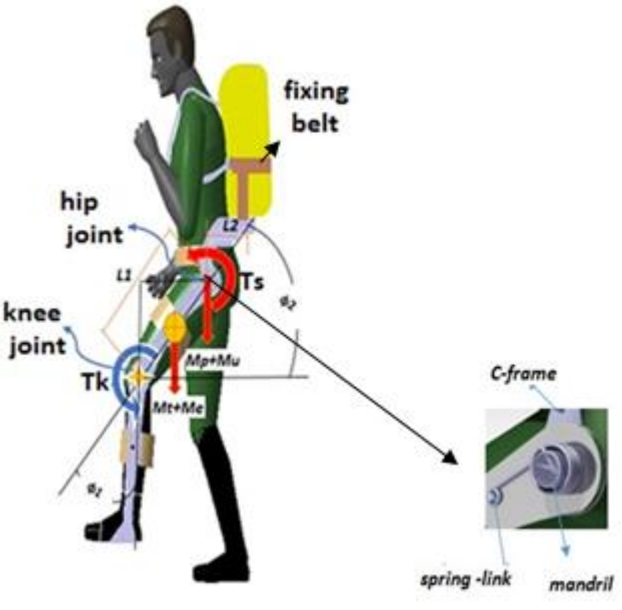


Figure.5. Torque and load distribution with cut section of 3D model of hip joint-spring interfaces (right)

$$T_K = (Mt + Me)\frac{L1}{2}(\cos\phi 2) + (Mp + Mu)L1\sin\phi 1 - Tc \text{ ………… (8)}$$

Where

Mt-- Mass of a thigh which is 10.5% of body weight.

Mp-- Mass at the backpack and other devices.

Mu-- Mass of the upper body part which is 55.1% of body weight.

Me-- Mass of exoskeleton link at the thigh (0.893Kg)

L1-- Length of the link at the thigh connection which is 23.2% of human height.

Tk-- Torque at the knee joint.

Tc-- Restoring/gravity compensating torque due to spring at the hip joint

$\phi 1$ -- Angle of hip joint flexion=$90^0 - \phi 2$ (Table-2)

$\phi 2$ -- Angle of knee joint flexion = maximum of 68^0(Table-2)

Table.2. Human joint range of motion

Joints	Human walking maximum-degree	Average male maximum-degree	Human with exoskeleton-degree
Knee flexion/extension	68/4	140/0	100/0
Hip flexion/extension	26/-10	120/-40	100/-15

Considering the pack spring system shown in figure-4 below as inverted pendulum, the stability equation is derived for the pack load by neglecting the horizontal load as compared to vertical down ward load due to gravity

$$I\ddot{\theta} = Mpgh\sin\theta - Tc \text{ … (9)}$$

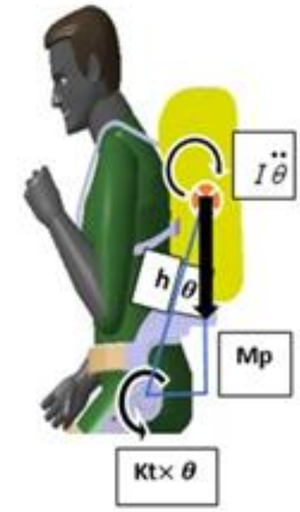


Figure.5. Stabilizing and destabilizing torques during motion

Considering small angle θ in equation (9) and after rearranging it gives an oscillating frequency in equation (12), finally a stability equation (13) is obtained as follows.

$$\ddot{\theta} + \frac{(Kt \times \theta - Mpgh)\theta}{I} = 0 \text{ ……… (10)}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{Kt\theta - Mpgh}{I}} \text{ ………… (11)}$$

For stability of the backpack, equation (12) holds true.

$$Kt\theta - Mpgh \geq 0 \text{ ………………… (12)}$$

$$Kt \geq \frac{Mpgh}{\theta} \text{ ……………………….. (13)}$$

Where. Kt is torsional spring stiffness, θ -is dynamic deflection of the spring in revolution or same as the angular shift of the pack load's center of gravity, g –is acceleration due to gravity and h –is distance between center of gravity of pack load and spring mandrel center

VII.TORSION SPRING DESIGN

Custom based special spring design has been adopted by looking the need statements and space availability at the hip joint and keeping in mind the ergonomics requirements while walking. The two end leg arrangements are one radial over center leg and one tangential leg are selected to fulfill the current requirements. The primary stress in torsion spring is the bending stress and it is given below in equation (14) where M is the bending moment due to the load of the thigh (10.5% of body weight = 6.7Kg) about hip joint, in this paper 75Kg human weight is taken for the entire analysis. The Wahl's stress factor K with spring index c is given in equation (15).High quality carbon steel material is selected with allowable bending stress of $\sigma_{all} = 1020 Mpa$ and Modulus of elasticity of $E = 205 \times 10^3 Mpa$

$$\sigma_b = \frac{32MK}{\pi d^3} \ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

$$K = \frac{4c^2 - c - 1}{4c^2 - 4c} \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

$$\theta = \frac{1}{2\pi}\theta_{rad} = \frac{ML_w}{2\pi EI} \ldots\ldots\ldots\ldots \quad (16)$$

$$\theta = \frac{1}{2\pi}\left[\frac{M}{E}\left(\frac{\pi D N_a}{\pi d^4 / 64}\right)\right] \ldots \quad (17)$$

$$\theta = 10.2\left(\frac{MDN_a}{d^4 E}\right) \ldots\ldots\ldots \quad (18)$$

To account for spring friction between the coils equation-(18) becomes

$$\theta = 10.8\left(\frac{MDN_a}{d^4 E}\right) \ldots\ldots\ldots \quad (19)$$

Based on the design requirements, space and compactness, design parameters are selected such as Coil mean diameter D=50mm, spring wire diameter d = 5mm, spring index c =10 and number of spring turns Na =4 has been considered. Hence the calculated bending stress and angular deflection are shown below:-

$$\sigma_b = 694 Mpa < \sigma all(1020 Mpa) \ldots\ldots\ldots \quad (20)$$

$$\theta = 0.132 rad\left(7.6^0\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

In addition to the above calculation more detail design simulation of torsion spring has been verified using Inventor 2017 Software as depicts in **Appendix** of last section.

VIII. RESULT AND DISCUSSION

In this result section the overall design that has been shown in the previous sections will be verified and presented by showing the significance of increasing weight of the backpack and the determination of optimal height of the load at the backpack of the soldier.

To verify the height and the weight variations on the stability of load and torsional stiffness of the spring which is used to gravity compensate the pack load, the equation of stability which determine the border line between destabilizing and stabilizing moments is iterated, it is done for different values of pack load and height difference between center of gravities of load and the user, finally the results are plotted by calculating the height differences from the center of gravity of the load and the central point of the hip joint.

The corresponding center of gravity differences between the load and the load carrying person (center of gravity = 57% of its height) are calculated as (256, 356, 40, and 0) mm. To keep the load in a stable upright position, a restoring moment is produced by a torsion spring with springs torsional stiffness with respect to the height and load differences as shown below in figures (4 -7).by combining the response of torsional effect with respect to the height and load variations the new exoskeleton load assistive mechanism has been designed to takeoff or gravity compensate the load while the soldiers are in long marching with heavy loads.

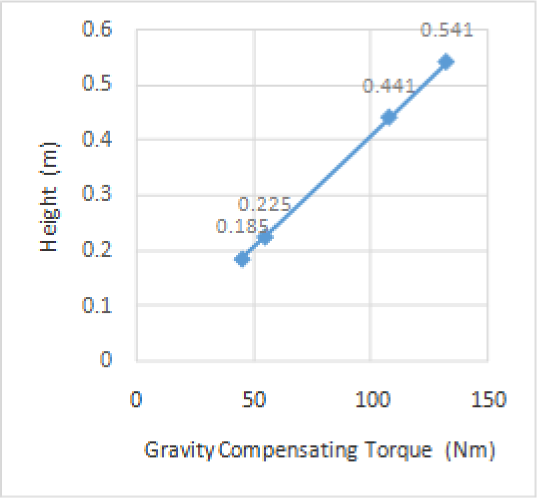


Figure.4. Competition of gravity compensating torque and height variation of the load from center of gravity of the soldier while carrying 25Kg of load.

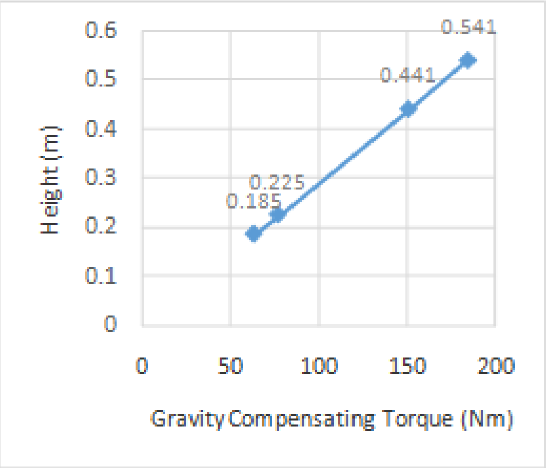


Figure.5. Competition of gravity compensating torque and height variation of the load from center of gravity of the soldier while carrying 30Kg of load.

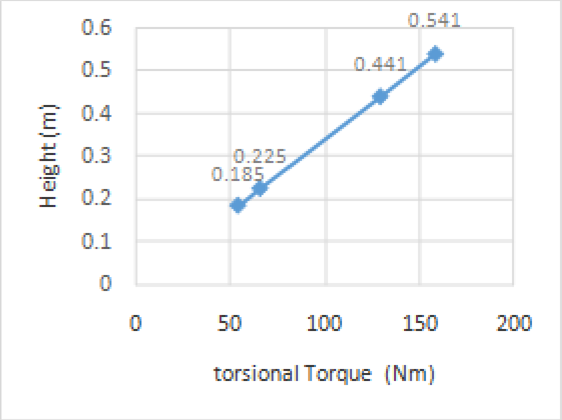


Figure.6. Competition of gravity compensating torque and height variation of the load from center of gravity of the soldier while carrying 35Kg of load.

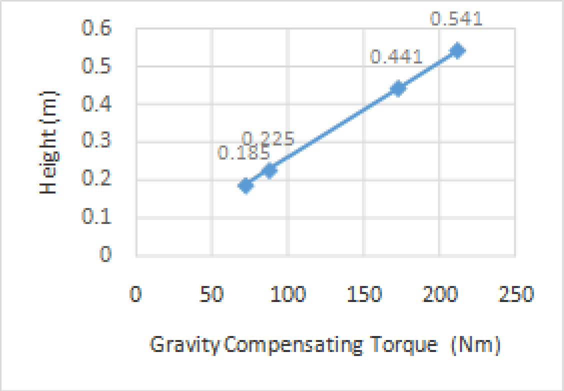


Figure.7. Competition of gravity compensating torque and height variation of the load from center of gravity of the soldier while carrying 40 Kg of load

Competition of the torque at the knee joint by taking the gravity compensation torque into consideration as shown in figure 8 leads to an effective result in three ways by firstly achieving the stability equation, secondly load compensation due to stored energy in the coiled spring and finally helping in an efficient selection and utilization of motor torque at the knee joint by avoiding an offset torque due to ground reaction force. Generally as the load increases, torque at the knee joint will also increase which shows the effect of using gravity compensating mechanism that reduces the torque requirement at the knee joint, when the required values of Tk increases, the torque compensating mechanism will help in tracking extra torque at the hip joint during stance phase of walking (foot contact to ground), inversely during swing phase(foot in air) the stored energy in the spring at hip joint will advance the thigh forward.

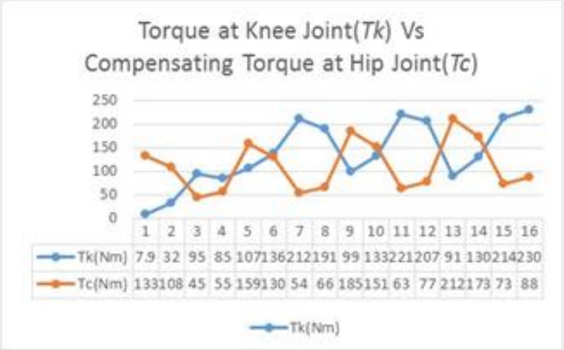


Figure.8. Effect of gravity compensating torque on knee joint torque during walking at different height and load variation

Figure (9) below shows the combined effect of height (541,441,185and 225mm) and mass (25, 30,35and40 Kg) variation on load carrying capacity by augmenting the torque at the knee joint due to the effect of gravity compensating torque, as the center of gravity between the load and the load carrying soldiers increases, the compensating torque will also increases thus decreasing the torque required at the knee joint. Similarly figure 10 shows the torque requirement at knee joint with and without considering the effect of load compensating device.

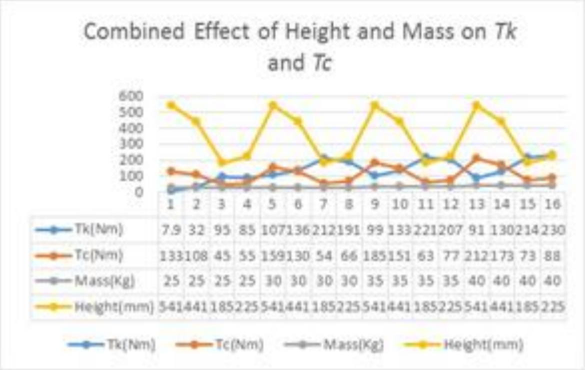


Figure.9.Combined effect of gravity compensating torque on knee joint torque at different height and load variation

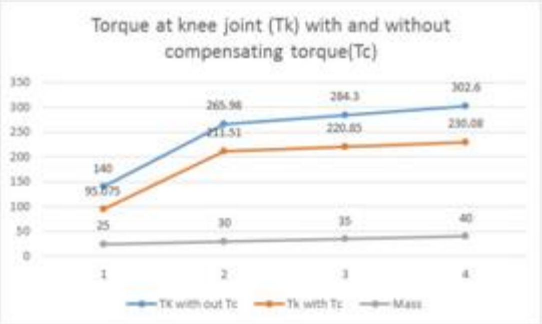


Figure.10.Evaluation of knee joint torque with and without Gravity compensating torque at selected height and masses.

FEA (finite element analysis) results are shown in figure (11) for the half part of the c-frame load supporting platform, in this design C –frame is taken as the worst scenario that must be checked, hence the advantage of using a curved beam helps in carrying the load with low stress, the maximum stress and deflection computed as $2.06\times10^{7}\,N/m^{2}$ and $0.215mm$ respectively for aluminum material having a yield stress of $9.5\times10^{7}\,N/m^{2}$ which is in a good agreement.

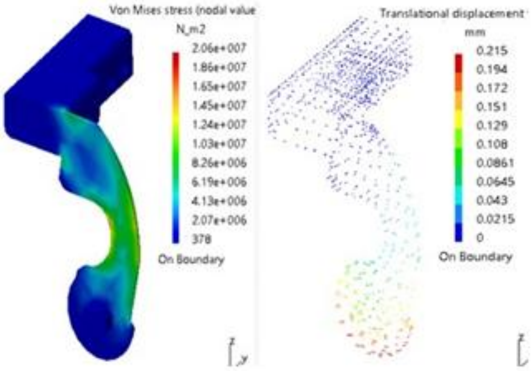


Figure.11.Fnite Element Analysis results of Stress (left) and Deflection (right)

IX. CONCLUSION

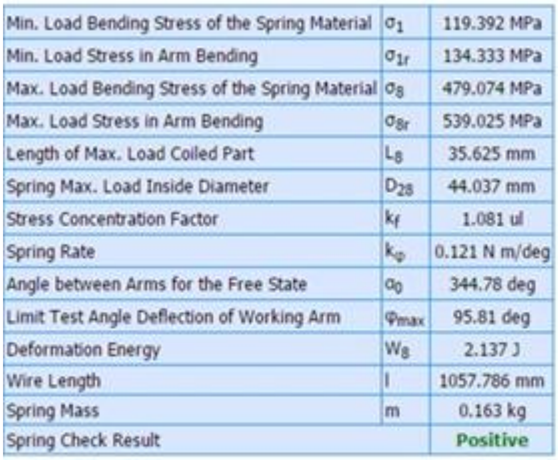
The work presented in this paper focuses on designing an assistive device or load carrying exoskeleton robotic suit for soldiers while travelling a long distance with a heavy loads, by adopting the digital human modeling (DHM) software, the anthropomorphic design architecture has been implemented to match the human joints with the exoskeleton joints while assuring an interference free product. In this design Knee joint is selected as active joint since most of the load is concentrated at this joint, but due to heavy loads carried during a mission it is difficult to raise the load easily with the help of the knee joint torque only, hence leg exoskeleton and additional gravity compensating platform which works based on torsion spring is adopted to overcome the offset torque at the knee joint because of ground reaction force. This mechanism works together with leg exoskeleton to reduce the torque required by the actuators. In the result section it has been made various iterations regarding the combined effect of gravity compensating torque and toque at the knee joint with respect to the height and load variations during walking, from these results the effective utilization of gravity compensating torque has been shown to help in minimizing the torque required at the knee joint while supporting the load. The obtained torque results are an indication in selecting an appropriate actuator torque in the future phase of this work, the variation of placing the loads at the pack with respect to center of gravity has shown an optimum location of placing the load to be slightly near to the center of gravity of the wearer so this location has considered in the designed concept model. Finite element analysis of components has been verified for deciding the effectiveness of the structure prior to manufacturing phase. Finally a comparison has been made for the actual torque required at knee joint, firstly without considering the effect of gravity compensating torque an average result was found as 248.32 Nm and by considering the effect of gravity compensating torque it is found to be 174.4 Nm which is 29.8% reduction.

X. FUTURE WORK

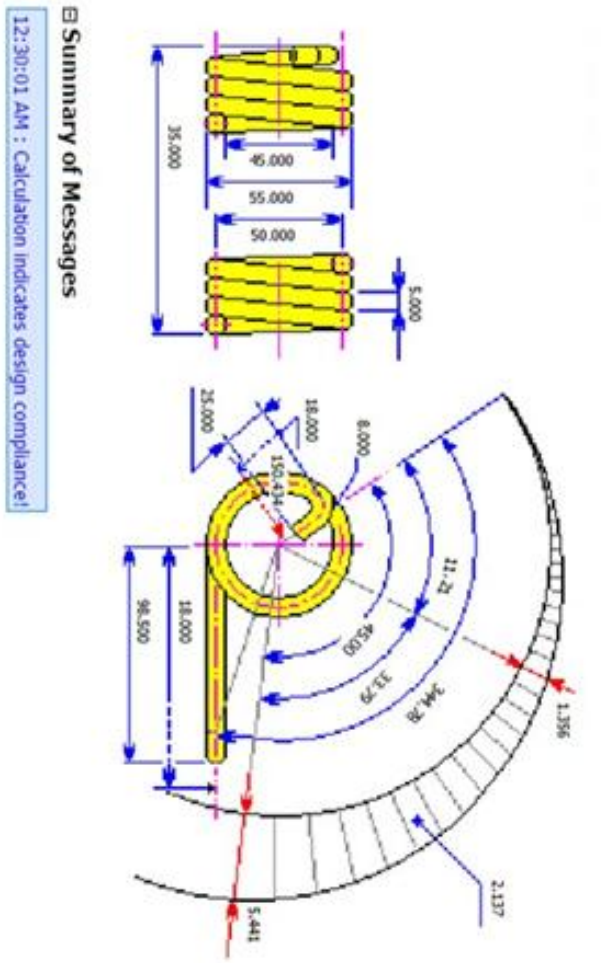
The work presented in this paper is the first phase of this paper which only focuses on the mechanical design of components and evaluation of proper load placement as well as torque compensation mechanism, hence control and actuation design will be considered as a second phase for the future work of this study.

APPENDIX

Torsion spring design parameter results
(Inventor 2017 Software)



Min. Load Bending Stress of the Spring Material	σ_1	119.392 MPa
Min. Load Stress in Arm Bending	σ_{1r}	134.333 MPa
Max. Load Bending Stress of the Spring Material	σ_8	479.074 MPa
Max. Load Stress in Arm Bending	σ_{8r}	539.025 MPa
Length of Max. Load Coiled Part	L_8	35.625 mm
Spring Max. Load Inside Diameter	D_{28}	44.037 mm
Stress Concentration Factor	k_f	1.081 ul
Spring Rate	k_φ	0.121 N m/deg
Angle between Arms for the Free State	α_0	344.78 deg
Limit Test Angle Deflection of Working Arm	φ_{max}	95.81 deg
Deformation Energy	W_8	2.137 J
Wire Length	l	1057.786 mm
Spring Mass	m	0.163 kg
Spring Check Result		Positive



⊟ Summary of Messages

12:30:01 AM : Calculation indicates design compliance!

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