Ergonomic support system for construction worker’s hand arm for lifting tasks

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Abstract. In this paper, a novel passive arm exoskeleton is introduced to assist the construction workers in load lifting/carrying tasks. The exoskeleton is designed based on torsion springs to generate assistive torque at the elbow and wrist joint and can fully support the weight of 8 kg task load. Static simulation of the springs and arm bracing was performed to check the correctness of the design parameters in ANSYS. The exoskeleton is extremely lightweight, economical, and easy to use as it provides a novel locking arrangement, which may allow workers to instantly disconnect the springs as per their need, making it highly suitable for the construction workers.

Keywords: Passive exoskeleton, Arm exoskeleton, torsion spring, arm bracing, assistive torque

1. Introduction

The construction industry is considered to be one of the most rapid-growing industries in India. With this dynamic growth in construction and other industrial sectors, the labor force has risen noticeably [1]. In developing countries construction is mostly dependent on manual tasks. However, the factors like lack of proper gear and equipment, poor working conditions, prolonged working hours with insufficient rest periods in between have not changed significantly [1]. A Study showed work-related Musculoskeletal disorders (WMSD) are one of the most common physical ailments, with an estimated prevalence of 77% in construction workers and furthermore 27.9% of the participants experienced symptoms of WMSDs in the upper body, including the neck, while 11.8% had symptoms at the wrist joints [2]. In fact, bricklayers were found to be the most prone to upper limb disorders (58.2%) [2]. Various studies manifested that repetitive hand and wrist movement accompanied by heavy load lifting/carrying tasks contributed to the development of musculoskeletal disorders. The construction and other industrial work involve a gamut of tasks like lifting and carrying a platter full of bricks or concrete, carrying bags of cement/wheat, loading/unloading of goods from Vehicles and carts, which notably contribute to the development of WMSDs. These disorders resulted in the hampered efficiency and productivity, loss of work, delayed healing of injuries, and disability. Therefore, it is a challenge for ergonomic designers to develop economical equipment, which may be used to improve productivity and reduce the risk of such WMSDs.

In recent years, the integration of exoskeletons to the construction and manufacturing industries is emerging as a potential solution for preventing the WMSDs. Wearable exoskeletons are devices that work in tandem with the user and act as amplifiers that augment, reinforce, or restore human performance. Exoskeletons equipped with external power sources, sensors, and actuators are classified
as active whereas passive exoskeletons use materials, springs, and other mechanical elements to store energy and assist the user. Several active exoskeletons have been developed for assistance during industrial tasks, rehabilitation purposes, and strength augmentation. A 7-DOF upper-limb exoskeleton with a newly designed cable-driven differential mechanism with bilateral structure was developed for post-stroke patients. Its performance was checked using surface EMG signals to understand the intention of the muscles of the user [3]. Another active upper-limb exoskeleton was developed for construction operations. This upper limb exoskeleton comprised of torque sensors to detect arm movement and was installed at the end-effector of the air-balancer [4]. A lightweight, upper-limb active exoskeleton was developed to assist user during lifting tasks. This exoskeleton used a wire driven mechanism to provide assistive torque for the elbow and shoulder joints and was capable of supporting a load of 10 kg. Bowden cables, wires, and motors were employed for the purpose of torque transmission. A voice-activated control was integrated into the device to allow better usage of the device [5]. Even though active exoskeletons are believed to provide more reactive and precise assistance, they lack reliability and energy efficiency. These limitations have hindered their applicability in industrial tasks. Therefore, several passive exoskeletons have been developed [6] and commercialized to serve the purpose and due to the absence of sensors, actuators, and power sources, they are much more durable and affordable. A passive exoskeleton for upper limb assistance in static holding tasks used springs mounted in support arms to compensate for the load. It had a total weight of 11 kg and was designed to be worn as a backpack. The effects of using this device on the upper limb muscles for overhead tasks were closely studied [7]. A well-known passive exoskeleton Hyundai vest exoskeleton (H-vex) was recently developed to provide assistance to the workers in manufacturing plants for overhead tasks. The device weighed 2.5 kg and used a multi-linkage spring mechanism which stored and dissipated energy according to the motion of the user’s arm. H-vex offered assistive torque and support to the shoulder joint to delay fatigue of the arm muscles [8]. Other commercially famous passive devices are MATE, SuitX, ExoVest, which are still priced at thousands of USD, making them extremely unaffordable for workers. Therefore, in the present study, it was aimed to develop an augmentation exoskeleton for hand-arm, which could provide a viable solution for the construction and small-scale workers. The modelling targeted the lifting tasks due to the excessive requirement of it in these industries. Major emphasis was laid on keeping it highly affordable, reliable so it does not hinder the natural movement of the limbs.

2. Methodology
Considering the limitations of existing exoskeletons, the key idea while designing the exoskeleton was to keep it lightweight and economical so that it could reach the masses. It was achieved by using purely mechanical elements to produce a reliable and robust design. In the process of lifting a load, the motion in the upper arm mainly depends on the wrist, elbow, and shoulder joints. Thus, the design mechanism of this exoskeleton is cautiously developed to avoid hindrance in the DOF of these joints [9]. This was aimed to provide overall comfort and unhampered motion of the user’s hand-arm system. From the feedback given by the construction workers, it was inferred that while carrying a platter full of bricks or cement the elbow and wrist joints & muscles are frequently strained. Therefore, this design was successively iterated to reduce the fatigue developed on these joints while performing these tasks, to provide improved productivity, and to safeguard the user from MSDs of wrist and elbow joints.

In the present design of the exoskeleton, the purpose of storing energy was in a way that could provide an assistive torque to the user by torsional springs. Torsional spring exerts a torque [10][11] when its legs are deflected in a way that tends to reduce/increase the size of the spring. Preliminary designs were mainly aimed to assist the elbow joint. In the beginning, the concept of the design consisted of a set of torsion springs with its legs being attached to the upper and lower arm bracing respectively. These springs were cased inside a box-like structure position right above the elbow joint as shown in Figure 1(a). After closely comprehending the working of this design it was noticed that the position of the springs would hinder the motion of the arm. Therefore, in the next iteration, the device consisted of two metal bars that were connected by the means of a torsion spring. The legs of the spring were force-fitted into the metal arm bars, which ran along the length of the arm on either side (Figure 1(b)). These
arm bars were connected to arm bracings to provide support and comfort. This design may successfully tackle the shortcomings faced by the previous idea as the position of the spring did not hamper the kinematics of the arm. Furthermore, the flexibility to engage and disengage the elbow springs as per the user’s need without removing the whole of the device seemed vital as in practical working conditions the user performs a gamut of tasks and the assistance provided by the exoskeleton might not be desirable at all times. So, the springs can be disconnected without taking off the exoskeleton when the natural motion of the arm is desired. Therefore, in the next iteration, it was achieved by the use of novel torsion springs and locking arrangement which allows the user to disconnect the springs from the rest of the frame. To achieve this, changes were made to the lower arm bracing and the leg of the elbow spring. Initially, the lower leg of the spring was extended and formed into the shape of a hoop, which was designed to pass through the slot provided in the lower arm bar. This arrangement was locked by the means of 2 corks as shown in Figure 1(c). Later these corks were replaced with a hinged pin mechanism and a helical spring. This change in the design provided much better handling and allowed the user to lock and unlock the elbow springs with simplicity. In the final iteration, a wrist support mechanism was developed and integrated into the overall design (Figure 1(d)). Based on the discussion with construction workers, the load lifted by the user tends to force the hand downwards, which causes pain and discomfort in the wrist as the frequency of the lifting/carrying task increases. The wrist support mechanism provides upward assistance to the back of the hand only when the lifted weight forces the downwards, without hindering the natural movement of the wrist joint in the remaining directions. The wrist support was connected with the lower arm bracing. The detailed working of these mechanisms is discussed in detail in the following sections.

Figure 1. Design Iterations performed to reach on the final design.

3. Final Design
This section focuses on the detailed description of the dimensions and materials selected for the components of the assistive device (Figure 1(d)). These were achieved after all the iterations mentioned in the previous section. The metal arm bars provided the basic frame for this device and proposed to be made up of Aluminium alloy 6061. Aluminium alloy 6061 was selected as it is lightweight, corrosion-resistant, and offers excellent mechanical properties [12][13]. The length of the lower arm bar was chosen from the mean length of the arm as per the average height of a male [14][15]. The supporting arm bracings and wrist support are proposed to be made of PLA. PLA was selected as the material for the arm bracings and wrist support as it can be easily 3D printed and, offers high mechanical properties [16][17] and affordability. The lower arm bracing has three pins on each side, which allows smooth motion of arm bars when the system transitions between locked and unlocked conditions. Keeping in
mind that all the assistance generated in this device comes through springs, Music Wire ASTM A228 was selected as the spring material as it has the highest tensile strength among wrought carbon or non-alloy steels. It has high mechanical properties and unmatched durability [18]. The dimensions of the major components are mentioned in Table 1.

Table 1. Dimensions of the major components.

| Parts                      | Dimensions | Material            |
|----------------------------|------------|---------------------|
| For Elbow spring           |            |                     |
| Wire diameter              | 3 mm       | Music Wire ASTM A228|
| Inner diameter             | 12 mm      |                     |
| Outer diameter             | 18 mm      |                     |
| Number of turns            | 5          |                     |
| Leg length                 | 6 mm       |                     |
| Mandrill Diameter          | 43 mm      |                     |
| Mandrill length            |            |                     |
| For Wrist support spring   |            |                     |
| Wire diameter              | 1 mm       | Music Wire ASTM A228|
| Inner diameter             | 4 mm       |                     |
| Outer diameter             | 6 mm       |                     |
| Number of turns            | 3          |                     |
| Leg length                 | 10 mm      |                     |
| Mandrill diameter          | 3 mm       |                     |
| Mandrill length            | 60 mm      |                     |
| Upper arm bar length       | 250 mm     | Aluminium alloy 6061|
| Lower arm bar length       | 256 mm     |                     |
| Weight of arm bar (Upper and Lower) | 77.07 grams | Aluminium alloy 6061|
| Weight of bracing (Upper and Lower) | 92.12 grams | PLA              |
| Weight of arm bar (Upper and Lower) | 106.02 grams |                     |
| Weight of bracing (Upper and Lower) | 86.21 grams |                     |

4. Stability analyses and Modifications in the final design based on simulation

To evaluate the stability of the proposed model of this assistive device the analyses of force and stresses were carried out for the different components of the final exoskeleton based assistive device for lifting tasks. Structural strength analysis of the different components experiencing stresses was done with the help of ANSYS 2016 software to verify the design's correctness. The analysis was carried out in the following steps:

4.1. Step 1:
Static structural simulation of the elbow spring with a fine mesh of 1 mm was performed. One end of the spring was constrained as fixed support while a load of 120N was applied to the other end of the spring. The force applied on the spring was carefully calculated based on the weight of 8 kg which is to be supported by the elbow springs and the average arm length of a male to replicate the actual loading scheme that the spring would experience due to the moment produced by 8kg load on the elbow joint. The total deformation, directional deformation, and equivalent stress are shown in Figure 2(a), 2(b), 2(c) respectively. The results of this simulation revealed the stability and correctness of the design parameters as the stresses developed were less than the yield stress of the material thus resulting in elastic
deformation.

Figure 2. (a) Total deformation, (b) Directional deformation and (c) Equivalent Von-mises stress developed in the elbow spring.

4.2 Step 2:
The lower arm bracing was studied and static simulation was performed on it to check the correctness of the design. It was pretty evident from the design that the green pins on the sides of the bracing would be subjected to the maximum stresses, therefore the whole bracing was taken as fixed support, and to study the stresses developed on the pins of 4mm diameter, the mesh size was taken as 1mm and a load of 80 N (to provide a factor of safety) was applied to pins of one arm bracing. The results revealed that the deformation caused in the pins was close to the plastic deformation range.

4.3 Step 3:
The diameter of the pins was increased to 6mm and the simulation was performed using the same loading scheme. The total, directional deformation and equivalent stress on the remodeled bracing are shown in Figure 3(a), 3(b), 3(c) respectively. It should be noted that support belts passing through the slots in the arm bracing and the metal bar are aimed to allow the user to fasten the exoskeleton on the arm. The load distribution taking place through the means of these belts and the elbow spring mandrill is not taken into account while performing the simulation on the arm bracing. Even after these assumptions, the results of this simulation revealed the correctness of the design parameters of arm bracing, and the developed stresses did not exceed the yield limit.

Figure 3. (a) Total deformation, (b) Directional deformation and (c) Equivalent Von-mises stress developed in the lower support system.
4.4 Step 4:
Static simulation for the wrist support spring, with a fine mesh of 1mm was performed. A load of 13 N was applied to one spring of the wrist support since it is approximately equal to the force exerted on the spring when 8kg weight is lifted. The intuition behind this load was that wrist support is only provided to prevent the discomfort caused to the wrist while lifting/carrying a load. The results for this analysis i.e. Total and directional deformation and equivalent stress are shown in Figure 4(a), 4(b), 4(c) respectively. The results indicated the correctness of the design. The above result can be interpreted as when the load lifted by the user, the wrist support would reduce the strain on the wrist joint while the assertive torque to support the load would only be provided by the elbow spring.

![Figure 4. (a) Total deformation, (b) Directional deformation and (c) Equivalent Von-mises stress developed in the wrist support spring.](image)

5. Working and Function
The overall working of this device and the individual functioning of the components of the exoskeleton is discussed in this section. This device uses the concept of storing energy from the extension of the arm but assists in load-carrying tasks as well. When the user expands the arms to lift the load, the energy gets stored in the springs which in turn assists the user in lifting the load. It also assists the user when the lifted load is carried away as the weight on the arms tends to gravitate it downwards disturbing the leg of the springs from their equilibrium position thereby resulting in the desired assistive torque. The functioning of each part of the exoskeleton is discussed in the following sections.

5.1 Arm Bars and Elbow Spring:
The elbow spring is made in such a way that one of its legs is extended and force-fit into the upper arm bar as shown in Figure 5(b) while the other leg of the spring is extended and made into a circular hoop which is made to pass through the slot in the lower arm bar as shown in Figure 5(a). The hoop is provided in the leg of the spring as in fig 5c to facilitate the locking mechanism. Together the arm bar forms the main frame of the exoskeleton while the springs generate the desirable assistive torque.
5.2 Wrist Support:
When the user lifts the load, it forces the hand to bend downwards which taxes the wrist joint muscles. The wrist support provided in this exoskeleton consists of a fixed structure that is connected to the lower arm bracing and a movable support structure which is connected to the fixed structure as shown in Figure 6 (a) by the means of 3 torsion springs (Figure 6 (b)). The legs of the spring are in equilibrium position when the movable support structure is at the same level as the fixed structure. When the lifted weight tends to gravitate the hand downwards, the movable structure is pushed down and the legs of these springs are disturbed from their equilibrium position. Due to this, the spring applies an assistive torque which supports the wrist and avoids discomfort.

5.3 Arm Bracing:
These PLA made lower (Figure 7(a)) and upper (Figure 7(b)) bracings are lightweight and easy to manufacture. The main function of these bracings is that it provides the required support to the arms and connects the arms to the main frame of the exoskeleton. It can also be provided with padding on the inside to impart better comfort to the user.

5.4 Locking Arrangement:
To connect the springs with the frame, the user applies a force on the lower arm bars in the region provided between the second and the third green pin, forcing the arm bar to slide on the green pins. As the bar moves inwards it compresses the spring that is closely wound on the mandrill of the elbow.
spring, with its either ends in contact with the respective arm bars (here the spring is extended out to
the end of the mandrill for visualization purposes only) and the hinged lock pin moves along with the
bar. When the arm bar has completely moved in Figure 8(a), the hoop of the elbow spring passes
through the slot provided in the bar. The exoskeleton is designed in such a way that when the bar
reaches the extreme position the lock pin slides inside of the hoop in Figure 8(b). Therefore, this
action locks the leg of the spring with the arm bar, making the exoskeleton ready to use.

Figure 8. Locked Assembly arrangement (a) Top View (b) Isometric View.

5.5 Unlocking Arrangement:
When the user feels the need to disconnect the springs as per need, it can be performed by applying
an upward thrust on the lock pins. Doing this would push them out of the hoop and the compressed
helical spring between the two arm bars would push the arm bars to the extreme ends of the green
pins (Figure 9(a)). The hoop of the elbow spring would no longer be in contact with the arm bars
(Figure 9(b)) thereby, allowing the free movement of the arm without taking off the whole device.

Figure 9. Unlocked Assembly arrangement (a) Top View (b) Isometric View.

6. Conclusion and Future Scope
The proposed design can be used to assist the workers during lifting and load-carrying tasks which are
very common in industrial work. The design uses a spring-based mechanism to transmit torque to the
elbow and wrist of the wearer. On comparing it with Hyundai’s H-Vex, the overall weight of device on
each arm would be much less than 1kg which is lower than 2.5 kg H-vex[8], which is considered as one
of the lightest existing exoskeletons. The H-vex like many other existing devices, provides assistance to
the shoulders, while this design supports elbow and wrist muscles for lifting/load carrying activities.
This device is extremely economic and would cost much less than 100 USD, while the H-vex which is considered as one of the most cost-effective exoskeletons, is still priced at 5000 USD. Due to the marginal cost, this design can be made available to all small-scale construction and industrial workers. It can fully support a load of 8 kg i.e., it can provide adequate assistance for general construction and industrial tasks. Therefore, the extreme lightweight, simplicity of design, low cost, and unique lock-unlock arrangement account for the feasibility of developing it.

In this section, the future aspect of this design has been discussed. Due to the limitations of cost and durability, no electronic components have been used in this device. For instance, the locking/unlocking mechanism can be automated by the use of stepper motors or microcontrollers. More emphasis can be laid on the locking mechanism and a lever or strap which joins the two hinge pins together can be provided in order to unlock the whole arrangement with a single thrust instead of unlocking both the pins separately. This can improve the overall handling of the exoskeleton and provide a faster unlocking system. The design uses just one elbow spring but if this design concept is taken further, more elbow springs can be added after making suitable changes to the arm bars. This can increase the load-carrying capacity. Since this device targets the elbow and wrist only, suitable attachments can be introduced which might provide assistance to the shoulder muscles of the user.

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