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Design of a Passive Robotic ExoSuit for Carrying Heavy Loads

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Abstract— **In this paper, a soft upper-extremity passive robotic exosuit is presented. This exosuit intends to assist workers when they are carrying heavy loads. The feature of the proposed exosuit design is that it consists of a light plastic frame and a cable system mounted via joints on the frame. Polyethylene braid-style cables are used which have a high strength of extension up to 34kg and low deformability. Comparing to the rigid frame exoskeleton, the mass and the inertia of the cable are negligible. With the help of cable winding and locking mechanism, during the transporting phase of load carrying, the gravity of the load can be compensated by cables and redistributed on the shoulder and thigh. Hence the pressure of muscles on arm can be relieved. In order to have the optimal assistive effect, the positions of anchors and cable attachment points have been optimized. An experiment has been conducted with a preliminary prototype mounted on a mannequin test bench. Experiment result shows that with the help of this exosuit, the mannequin test bench can steadily hold its posture when a 10kg load is applied and meanwhile, its joint mobility is not affected when it is in the non-carrying-load mode.**

I. Introduction

Assistive robots have application in the industrial field as well as for patients and the elderly with mobility impairments. They free people from much labor and the burdens of many kinds of manual work. There have been many approaches to the reduction of labor that do not only fully assist but also partly aid workers, such as in the use of extremely heavy payload-oriented construction equipment, which is manipulated by humans. Manual or semi-automatic machine tools are mostly used in contemporary industries. In particular, without manpower, especially without the manipulability and mobility of human limbs, full automation will be incompatible with today's technologies. The assistive robotized devices have strong advantages given their unique features such as their outstanding physical performance, exceeding that of humans, and their agility. As a result, attempts to adopt these devices in the industrial field, especially at construction sites, indicate the use of feasible approaches to factory automation [1]-[2].

In the last decade, many researchers have conducted their research in the field of wearable assistive robots and several exoskeletons have been designed for the purposes ranging from leg orthosis and gait rehabilitation [3]-[9] to enhancing the physical ability of human [10]-[11]. While for the previous designs, rigid links are used for forming their structure and transmitting force to the users. However, the use of rigid components leads to several drawbacks. For example, the caused adding inertia effects which must be compensated by users or actuators, and the misalignment of the links will cause the discomfort and even dangerous injuries to the users.

By example, EXHAUSS offers a range of exoskeletons, each intended to relieve and protect operators, for various constraints related to handling or carrying loads or tools. In this design concept, springs are used for gravity balancing of carrying loads. However, the support mechanical system is relatively heavy, and the handling is not easy. Besides this, the gravity balancing is not uniform in the working volume of these assistive devices [12].

It should be noted that the assistive devices with cables for handling heavy objects have been proposed by STRONGARM (Fig.1) [13]. The handling systems with cables are light. However, the use of two cables limits the manipulability of the assistive device, i.e. the ability to compensate gravity forces in different positions. A system with several cables can resolve this problem and better distribute the loads on the shoulders.

Figure 1. STRONGARM assistive device

For solving the previous problems, several soft, suit-like exoskeletons (also known as "exosuit") have been proposed in recent years. Because of using soft materials like fabrics and cables, the exosuits much lighter than the exoskeletons, therefore, only a little inertia is added to the wearer's movement. Additionally, since there is no rigid joints or frames exist in exosuits, so there is no problem relating to the joint misalignment. Unlike conventional exoskeleton, exosuit does not contain any rigid elements which can transfer loads to the ground hence the wearers must sustain all the compressive forces by their own bones. Two prototypes of lower-extremity exosuit have been designed by researchers from the Wyss Institute for Biologically Inspired Engineering at Harvard University [14]-[16]. For the first design, the pneumatic actuators attach to the exosuit through a network of soft, inextensible webbing triangulated to attachment points, and torques are provided on the hip, knee, and ankle joint. And the second exosuit is fixed on the body by straps and actuated cables can generate moments at the ankle and hip with magnitudes of 18% and 30% of those naturally generated by the body during walking, respectively.

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Meanwhile, several researchers have also conducted their research on the exosuit for upper-limb rehabilitation [17]-[19] and power augmentation [20]-[21]. In these exosuits cables are anchored on user's body by light-weight bracelets or flexible suit and winding actuators are used for tensioning cables and provide moment on the upper-limb joint. However, for the mentioned upper-limb exosuits, although these designs have compliant joints and add little inertia to the users, they still some drawbacks. The first is, for some designs, actuators are rather mounted on the user's body but are mounted on the fixed frame or on the ground, which let the users only have very limited moving space. And for the portable designs, users must undertake the weight of motors and control system, hence the size of the motor should be relatively small which means limited torques can be provided.

Work-related diseases of muscle and skeletal system are prevalent among physically demanding labors. Despite the industrialization has already been proceeding for hundreds of years, the number of occupational diseases, as well as cumulative trauma disorders (CTD) caused by overwork, is still significant nowadays. They are caused by ergonomic factors of the work environment, such as physical overload, compulsive working postures, the local stiffness of definite muscle groups and an adverse microclimate [22]. When workers carry loads, the gravity and dynamic force of the load will induce quite significant moments to the elbow, shoulder and trunk joint which will lead to the fatigue and even injury of muscles like the bicep, anterior deltoid, spinal extensor etc. [23].

In order to reduce the moment generated by loads during transporting, in this paper, a passive exosuit for load carriage has been proposed. In this exosuit, polyethylene braid-style cables are used and attached to user's body through anchors and attachment points, which function as auxiliary muscles to compensate the gravity of load. A passive cable winding and locking mechanism has been designed for keeping cables in tension and holding user's position during load carriage. The weight of the cables is negligible and adds nearly zero inertia to users. With the help of the exosuit, gravitational forces induced by the load can be partially redistributed to the user's body where can uphold larger force like shoulder and leg and consequently the work of arm muscles will be relieved.

The paper is organized as follows. In the next part, the loads on the human arm due to the handling of a heavy object are presented. Then, the distribution of the suggested exosuit for relieving the fatigue of user's muscles is discussed. A CAD model for simulations of the exosuit was built and the cable attachment positions on the user are optimized. Finally, the experimental results carried out on a mannequin test bench are presented.

II. LOADS ON ARMS DUE TO A HEAVY OBJECT

A. Static Analysis of a Human Carrying Load

When a human carry load, at first the arms are expanded to lift and hold the load, and then transport the load to the destination. Hence during the transporting phase, human stays at a relatively firm posture and a constant speed, and the force acts on the body which induced by the load is primarily static force.

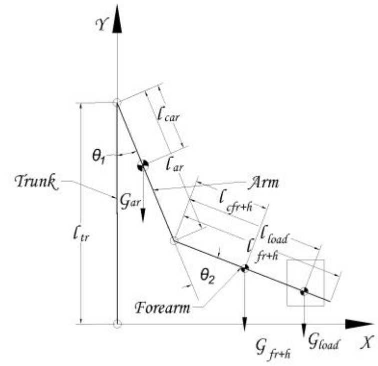


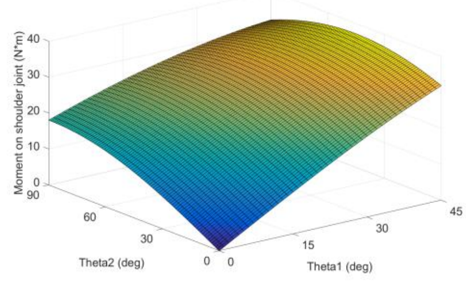
Figure 2. Static force analysis diagram when carrying load

Fig. 2 shows the planar diagram of a human carrying load. It can be seen that, while the human carrying load with only planar movement, his arm and forearm can be illustrated as a serial 2-DOF manipulator. The moments on the shoulder and elbow joints induced by the gravitational force can be calculated by:

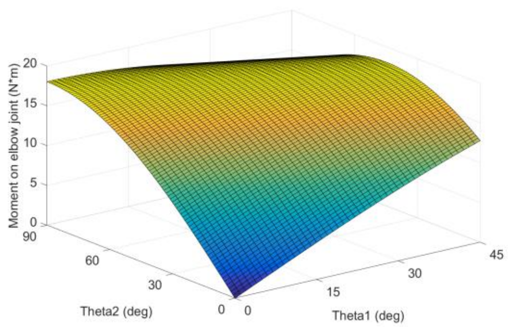
$$\begin{aligned} M_{shoulder}^{gravity} &= M_{elbow}^{gravity} + \left[(G_{fr} + G_{load}) l_{ar} + G_{ar} l_{car} \right] \sin\theta_1 \\ M_{elbow}^{gravity} &= (G_{fr+h} l_{cfr+h} + G_{load} l_{fr+h}) \sin(\theta_1 + \theta_2) \end{aligned} \tag{1}$$

where G_{load}, G_{fr+h} *and* G_{ar} are the gravity of load, forearm with hand, arm respectively; l_{fr+h}, l_{ar}, *and* l_{tr} are the length of the forearm with hand, arm, and trunk respectively; l_{cfr+h}, l_{car} are the distances from the center of gravity (COG) of forearm with hand, arm to the elbow, shoulder joints respectively; θ_1 is the shoulder extension angle and θ_2 is the forearm flexion angle.

From literature [24], we get the average body segment parameters of an adult male with 172.68cm height and 63.97kg weight as following: $G_{fr+h}=16.66N$, $G_{ar}=20.286N$, $l_{fr+h}=0.502m$, $l_{ar}=0.364m$, $l_{tr}=0.545m$, $l_{cfr+h}=0.203m$ *and* $l_{car}=0.1554m$. Using these parameters, the gravity moments on waist, shoulder and elbow joint when carrying 10kg load with different postures (θ_1=0°, $\theta_2 \in$ [0°, 45°], $\theta_3 \in$ [0°, 90°]) are shown in Fig. 3. It is shown that when carrying load with different postures, the gravitational moments on the joints are also different and these moments must be compensated by the muscle force.



(a) Gravitational moment on shoulder joint



(b) Gravitational moment on elbow joint

Figure 3. Gravitational moment on shoulder(a) and elbow(b) joint when carrying 10kg load with different postures

B. Design Concept of Passive Exosuit for Carrying Heavy Load

In this study, we intend to design a passive soft robotic suit to assist users for carrying heavy loads. This soft robotic suit is planned to have three features: 1) lightweight: the mass of the suit adds little extra inertia hence user's movement will not be impeded while wearing this suit; 2) compliant: the interface between user and suit is compliant so user will not be hurt due to the installation error or system failure; 3) passive: no motors and control system are comprised in the suit of which the size and mass may limit the mobility when wearing the suit.

When humans move their limbs, their muscles contract for generating tension forces, then the forces are transmitted to the skeletons through tendons hence moments will be generated on the articulations for moving their limbs. When human's limbs stay in a certain position, muscles can generate high tension force while keeping in the same length. In the proposed system, the function of cables is akin to the muscles in human. Therefore, a polyethylene braid-style cable with a diameter of 0.4mm is chosen which can bear load up to 34kg while having little deformation.

Another important part of the design is the interfaces between cables and user through which forces are transmitted from cables to the user. These interfaces are expected to have the feature of being compliable while holding their position. In our design, there are two types of interface: the first one is anchor through which cable is fixed to the user's body; the other on is the attachment point where the cable passes through. The anchors on the forearm and upper arm are plastic bracelets and rubbers are filled between them and wearer to provide comfortability. Two rubber pads and installed on the shoulders which have one anchor and two attachment points for each one. The other attachment points on the arm are fixed by hexagon-shaped webbings attached around the arms which are comprised of polyethylene cables and ring-shaped hubs. Besides, for the safety of users, silicone tubes are used as the housing of cable.

In order to let the soft exosuit adapt with different postures when reaching and lifting up the load as well as locking cables at certain positions when carrying loads, a cable winding and locking mechanism (Fig. 4) was designed. This mechanism includes a cable spool, a torsional spring and a ratchet mechanism. The cable spool links with the torsional spring and the ratchet. Torsional spring can provide a passive moment for the spool to wind up cable. A Ratchet mechanism is used as locking mechanism. While carrying loads, wearers can engage the locking mechanism by pressing the activation button installed on their thumb, then the pawl is pressed and enters into the gap between two teeth of the ratchet then the spool is stopped from moving and the generated cable tension can be used for compensating the gravity of load. In contrast, when the user is not carrying load and activation button released, the pawl will lift up and the spool can freely rotate. This is one of the simple solutions that has been developed. It is obvious that one can be found similar systems having the same functionality.

The 3D CAD model of the proposed design of exosuit with a human carrying a load shows in Fig. 5.

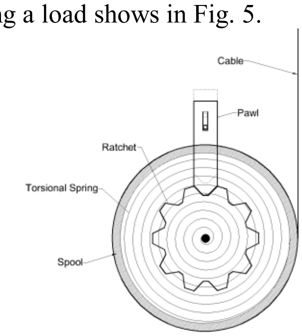


Figure 4. Cable winding and locking mechanism

Figure 5. CAD model of proposed design

III. SIMULATION & OPTIMIZATION

A. System Modeling

A planar diagram of the user wearing the exosuit system is shown in Fig. 6. In this diagram, two cables start from the anchors on the forearm and upper arm respectively and end at the cable winding and locking mechanisms fixed on the hip. The cable arrangements are as following: cable 1 starts form anchor on point 1, pass through attachment points on point 2, point 4, point 5, point 6, point 7, point 8; cable 2 starts form anchor on point 3, pass through attachment points on point 4, point 5, point 6, point 7, point 8. Before determining the moments induced by cables, we assume that the deformation of the cable is very tiny and negligible.

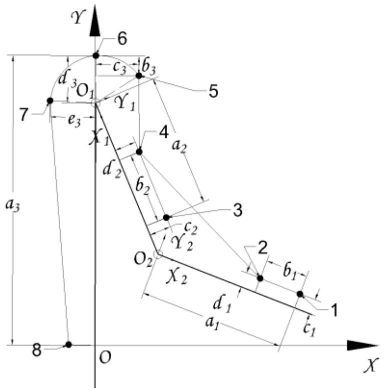


Figure 6. Planar static force analysis diagram when carrying load

As shown in Fig. 6, two local coordinate systems $X_1O_1Y_1$ and $X_2O_2Y_2$ are fixed on the upper arm and forearm respectively. The general coordinate of a point k on the global coordinate system can be calculated by:

$$\mathbf{p}_k=\begin{bmatrix} x_k \\ y_k \\ z_k \\ 1 \end{bmatrix}=\begin{cases} {}^{0}_{1}\mathbf{T}\cdot\mathbf{p}_{\mathbf{k}}^{(1)} \\ {}^{0}_{1}\mathbf{T}\cdot{}^{1}_{2}\mathbf{T}\cdot\mathbf{p}_{\mathbf{k}}^{(2)} \end{cases} \tag{1}$$

where $\mathbf{p}_{\mathbf{k}}^{(1)}$ and $\mathbf{p}_{\mathbf{k}}^{(2)}$ denote a point on the $X_1O_1Y_1$ and $X_2O_2Y_2$ respectively, and the transfer matrix ${}^{0}_{1}\mathbf{T}$ and ${}^{1}_{2}\mathbf{T}$ can be calculated by:

$${}^{0}_{1}\mathbf{T}=\begin{bmatrix} \cos(\pi+\theta_1) & -\sin(\pi+\theta_1) & 0 & l_{tr} \\ \sin(\pi+\theta_1) & \cos(\pi+\theta_1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^{1}_{2}\mathbf{T}=\begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_{ar} \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Thus, the global coordinate of point i is:

$$\mathbf{c}_{\mathbf{i}}=\begin{bmatrix} x_i \\ y_i \end{bmatrix} \tag{2}$$

$M^{cable}_{1-shoulder}$ and $M^{cable}_{1-elbow}$ denote the moments on the shoulder and elbow joint induced by cable 1 respectively, and $M^{cable}_{2-shoulder}$ denotes the moment on the shoulder joint induced by cable 2. They can be calculated by:

$$\begin{aligned} M^{cable}_{1-shoulder} &= [\mathbf{v}^*_{O_1 1}\times\mathbf{v}_{12}+\mathbf{v}^*_{O_2 2}\times(\mathbf{v}_{21}+\mathbf{v}_{24})+\mathbf{v}^*_{O_2 4}\times(\mathbf{v}_{42}+\mathbf{v}_{45})]\cdot T_1 \\ M^{cable}_{1-elbow} &= [\mathbf{v}^*_{O_3 1}\times\mathbf{v}_{12}+\mathbf{v}^*_{O_3 2}\times(\mathbf{v}_{21}+\mathbf{v}_{24})]\cdot T_1 \\ M^{cable}_{2-shoulder} &= [\mathbf{v}^*_{O_2 3}\times\mathbf{v}_{34}+\mathbf{v}^*_{O_2 4}\times(\mathbf{v}_{43}+\mathbf{v}_{45})]\cdot T_2 \end{aligned} \tag{3}$$

where $\mathbf{v}^*_{\mathbf{ij}}=\mathbf{c}_{\mathbf{j}}-\mathbf{c}_{\mathbf{i}}$ denotes the vector from point i to point j and $\mathbf{v}_{\mathbf{ij}}$ denotes the unit vector of $\mathbf{v}^*_{\mathbf{ij}}$.

Then the moments on joint i induced by all three cable tensions denoted as M^{cable}_i and can be calculated by:

$$\begin{bmatrix} M^{cable}_{shoulder} \\ M^{cable}_{elbow} \end{bmatrix}=\begin{bmatrix} M^{cable}_{1-shoulder}+M^{cable}_{2-shoulder} \\ M^{cable}_{1-elbow} \end{bmatrix}=\mathbf{J}\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} \tag{4}$$

where,

$$\mathbf{J}=\begin{bmatrix} \mathbf{v}^*_{O_2 1}\times\mathbf{v}_{12}+\mathbf{v}^*_{O_2 2}\times(\mathbf{v}_{21}+\mathbf{v}_{24})+\mathbf{v}^*_{O_2 4}\times(\mathbf{v}_{42}+\mathbf{v}_{45}) & \mathbf{v}^*_{O_2 3}\times\mathbf{v}_{34}+\mathbf{v}^*_{O_2 4}\times(\mathbf{v}_{43}+\mathbf{v}_{45}) \\ \mathbf{v}^*_{O_3 1}\times\mathbf{v}_{12}+\mathbf{v}^*_{O_3 2}\times(\mathbf{v}_{21}+\mathbf{v}_{24}) & 0 \end{bmatrix}$$

When wearing the exosuit, the moments induced by the gravitational force can be compensated by the moments generated by cables. Therefore, the cable tensions T_1 and T_2 can be calculated by:

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix}=\mathbf{J}^{-1}\begin{bmatrix} M^{gravity}_{shoulder} \\ M^{gravity}_{elbow} \end{bmatrix} \tag{5}$$

and then the force exerted on the shoulder by cables is:

$$F^{cable}_{shoulder}=(\mathbf{v}_{54}+\mathbf{v}_{78})(T_1+T_2) \tag{6}$$

B. Numerical Simulations

To investigate the cable tensions during the usage of the exosuit, in this section, simulations were done by using the model established in the previous section. The body segment data is the same as the one in section Ⅱ.A. The initial parameters with respect to the positions of anchors and attachment points are as following: *a_1=0.3m, b_1=0.1m, c_1=0.08m, d_1=0.08m, a_2=0.26m, b_2=0.1m, c_2=0.1m, d_2=0.1m, a_3=0.65m, b_3=0.1m, c_3=0.1m, d_3=0.1m and e_3=0.1m*.

Simulation results show that when a user carries 10 kg load with different arm postures ($\theta_1\in[0°,45°]$ and $\theta_2\in[0°,90°]$), the maximum tensions are 137N and 718N for cable 1 and 2, respectively. It can be seen that, for the maximum tension in cable 2, the limit of the max tolerable tension has already been passed. Besides, for some postures, the tension of cable 2 is negative which is not permissible.

Another thing must be concerned with is the force exerted on the shoulder by cables, since a large portion of force has been redistributed on the shoulder. Simulation results show that the maximum force on the shoulder is 1373N, and it is necessary to create a support system for protecting users.

C. Optimization of Design Parameters

It can be seen from the equation (5) that the relation between cable tensions and moment induced by the cable on joints are determined by the arrangement of anchors and attachment points. Then, as the cable tension forces increase, the forces react on the user will increase too. Hence, in this section, the arrangement of anchors and attachment points has been optimized to minimize the cable tension forces.

In the optimization, we take the system model built in section Ⅲ.A, and the 13 parameters to be optimize are a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2, a_3, b_3, c_3, d_3 *and* e_3 (as shown in Fig. 7). These parameters determine the positions of anchors and attachment points. For the possible postures of the user, we assume when users carry load, their back is always upright i.e.

$\theta_1 = 0°$. And the arm configurations are in the range of $\theta_1 \in [0°, 15°, ..., 45°]$ and $\theta_2 \in [0°, 10°, ..., 90°]$, which gives 40 possible postures. In this optimization, we are going to minimize the total cable tensions and force exerted on the shoulder when a user carrying 10kg loads with these 40 possible postures.

Another thing has to be concerned is the constraints. In this problem, there are two kinds of constraints which are:

(1) For all the configurations, cables must be always in tension i.e. cable tensions are always positive;

(2) The space constraints of the positions of anchors and attachment points.

So, the problem in this optimization can be formulated as:

$$\sum_{\theta_1}\sum_{\theta_2}\left(T_1 + T_2 + F_{shoulder}\right) + P \rightarrow \min_{a_1, b_1, c_1, ..., e_3}$$

subject to: $0.2 \le a_1 \le 0.3$; $0.01 \le b_1 \le 0.1$; $0.08 \le c_1 \le 0.13$;

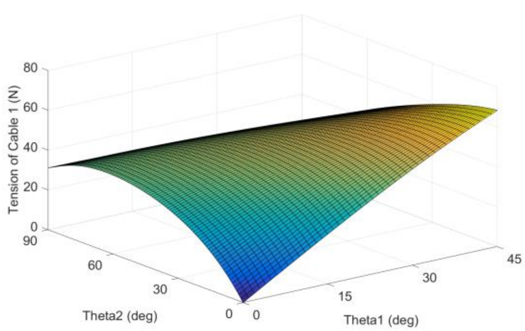
$0.08 \le d_1 \le 0.13$; $0.16 \le a_2 \le 0.26$; $0.01 \le b_2 \le 0.1$;

$0.1 \le c_2 \le 0.15$; $0.1 \le d_2 \le 0.15$; $0.55 \le a_3 \le 0.7$;

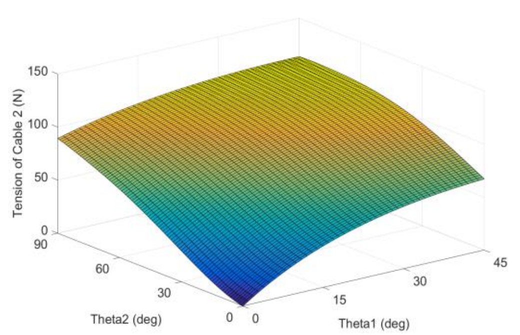
$-0.1 \le b_3 \le 0.1$; $0.05 \le c_3 \le 0.15$; $-0.1 \le d_3 \le 0.1$;

$0.05 \le e_3 \le 0.15$.

where P is a very large value to penalize the goal function when any of the cable tension is negative for all configurations.



(a) Tension of Cable 1



(b) Tension of Cable 2

Figure 7. Cable tensions when carrying 10kg load with different postures after optimization

The optimized parameters are the followings: *a_1=0.23m, b_1=0.1m, c_1=0.11m, d_1=0.08m, a_2=0.26m, b_2=0.01m, c_2=0.14m, d_2=0.15m, a_3=0.7m, b_3=-0.1m, c_3=0.15m, d_3=0m and e_3=0.05m*. With these parameters, the cable tensions with respect to different postures are shown in Fig. 7. The cable tensions have been drastically reduced after optimization, with maximum values of 68N and 114N for cable 1 and cable 2 respectively. Meanwhile, the maximum force exerted on the shoulder has also been reduced to 308N. Therefore, the optimization can increase the comfortability of the exosuit.

IV. EXPERIMENTAL TESTS

In order to evaluate the performance of proposed passive exosuit, an initial prototype of the exosuit was fabricated and mounted on the test bench (Fig. 8). The test bench was converted from a mannequin and the mobility of the arms has been ensured by adding spherical joints on the elbow and shoulder connections.

Figure 8. Mannequin test bench

To test the performance of the exosuit when the user is in different positions, several postures have been chosen for the experiments. For the shoulder extension angle, 0° and 30° were chosen, and for the forearm flexion angle 0°, 30°, 60°, and 90° were chosen. And for each posture, no load, 5kg, and 10kg load were put on the mannequin's arm. Then the cable tensions were measured.

Experiments showed that with the help of the exosuit, the mannequin test bench can hold the load steadily with different postures and different loads. The measured cable tensions with respect to the forearm flexion angle when shoulder extension angle is 0° and 30° are shown in Fig. 9 and Fig. 10, respectively.

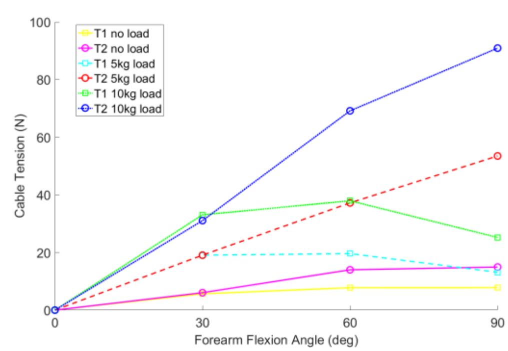


Figure 9. Cable tensions with respect to the change of forearm flexion angle (shoulder extension angle is 0°)

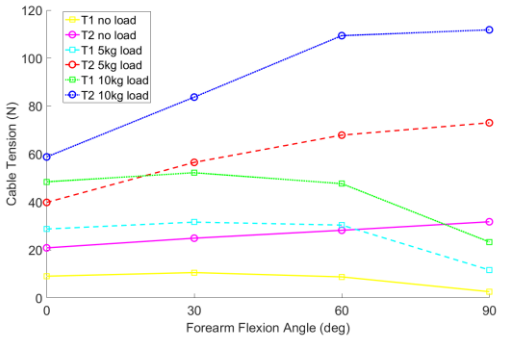


Figure 10. Cable tensions with respect to the change of forearm flexion angle (shoulder extension angle is 30°)

V. Conclusion & Future work

In this study, a passive exosuit has been proposed which intends to assist able human to carry heavy loads. The proposed exosuit presents a symbiosis of two systems; rigid support and cable system. The cable system is mounted on the rigid support permitting to compensate the gravitational force of a heavy load. The exosuit is made up of high-intensity polyethylene cables which are very light and add almost zero inertia to users. A cable winding and locking mechanism has been designed in order to keep cables in tension while users changing their postures and meanwhile stop the movement of the cables while users carrying loads. A static balancing model of the exosuit system was built to estimate the cable tensions and force exerted on the user's body. To optimize the performance and force exerted on the user by the exosuit, an optimization of the position of the anchors and attachment points of the exosuit was made. A prototype has been fabricated and tested via a mannequin test bench. The tests showed that with the help of the exosuit, the mannequin can hold different weights of loads steadily in different postures.

In the future, the interface between exosuit and human is planned to develop. Experiments with human and evaluation on the realistic tasks are also prospected in the near future.

References

[1] Writing, G. M., Lloyd-Jones, D., Adams, R. J., Brown, T. M., Carnethon, M., Dai, S., ... & Gillespie, C., Heart disease and stroke statistics--2010 update: a report from the American Heart Association. Circulation, 2010, 121(7), e46.

[2] Y. Zhang, V. Arakelian and J.-P. Le Baron, Design concepts and functional particularities of wearable walking assist devices and power-assist suits - a review. Proceedings of the 58th International Conference of Machine Design Departments (ICDM'2017), September 6-8, Prague, Czech Republic, 2017, pp. 436-441.

[3] Zeilig G, Weingarden H, Zwecker M, et al. Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study[J]. The journal of spinal cord medicine, 2012, 35(2): 96-101.

[4] Suzuki K., Mito G., Kawamoto, H., Hasega-wa Y., and Sankai Y., Intention-based walking support for paraplegia patients with Robot Suit HAL. Advanced Robotics, 2007, 21(12): 1441 – 1469.

[5] Kolakowsky-Hayner, Stephanie A., et al. "Safety and feasibility of using the Ekso™ bionic exoskeleton to aid ambulation after spinal cord injury." J Spine 4 (2013): 003.

[6] Veneman, Jan F., et al. "Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation." IEEE Transactions on Neural Systems and Rehabilitation Engineering 15.3 (2007): 379-386.

[7] Agrawal, Sunil K., Abbas Fattah, and Sal Banala. "Gravity balanced orthosis apparatus." U.S. Patent No. 7,544,155. 9 Jun. 2009.

[8] V. Arakelian, S. Sargsyan and M. Harutyunyan. Friction torque compensation in the balanced leg orthosis for robotic rehabilitation. Proceedings of the 8th European Solid Mechanics Conference (ESMC 2012). July 9-12, 2012, Graz, Austria.

[9] S. Sargsyan, V. Arakelian and S. Briot. Robotic rehabilitation devices of human extremities: design concepts and functional particularities. Proceedings of the ASME 2012 11th Biennial Conference on Engineering Systems Design and Analysis (ESDA 2012), July 2-4, 2012, Nantes, France.

[10] Garrec Ph., Coste F., Grygorowicz S., Perrot Y., Ponsort D., & Riglet A. (2013) Lower Exoskeleton. FR2981266 / WO2013057057. Pub. Date: 19/04/2013, Bulletin 13/16.

[11] Chu, A., Kazerooni, H., & Zoss, A. (2005). On the biomimetic design of the berkeley lower extremity exoskeleton (BLEEX). In Robotics and Automation, 2005. ICRA 2005, pp:4345-4352.

[12] Exhauss.com. (2018). EXHAUSS. [online] Available at: http://www.exhauss.com/fr_modelew.htm [Accessed 15 Jun. 2018].

[13] Strongarmtech.com. (2018). Products. [online] Available at: https://www.strongarmtech.com/ergoskeleton#v22 [Accessed 11 July. 2018].

[14] Wehner, Michael, et al. "A lightweight soft exosuit for gait assistance." Robotics and Automation (ICRA), 2013 IEEE International Conference on. IEEE, 2013.

[15] Asbeck, Alan T., Kai Schmidt, and Conor J. Walsh. "Soft exosuit for hip assistance." Robotics and Autonomous Systems 73 (2015): 102-110.

[16] Ding, Ye, et al. "Biomechanical and physiological evaluation of multi-joint assistance with soft exosuits." IEEE Transactions on Neural Systems and Rehabilitation Engineering 25.2 (2017): 119-130.

[17] Lessard S, Pansodtee P, Robbins A, et al. CRUX: A compliant robotic upper-extremity exosuit for lightweight, portable, multi-joint muscular augmentation. Rehabilitation Robotics (ICORR), 2017 International Conference on. IEEE, 2017: 1633-1638.

[18] Mao Y, Agrawal S K. Design of a cable-driven arm exoskeleton (CAREX) for neural rehabilitation. IEEE Transactions on Robotics, 2012, 28(4): 922-931.

[19] Xin Jin, Viswanath Aluru, Preeti Raghavan, Sunil K. Agrawal, "The Effect of CAREX on muscle activation during a point-to-point reaching task", Rehabilitation Robotics (ICORR) 2015 IEEE International Conference on, pp. 73-78, 2015.

[20] Xiloyannis M, Cappello L, Binh K D, et al. Preliminary design and control of a soft exosuit for assisting elbow movements and hand grasping in activities of daily living. Journal of Rehabilitation and Assistive Technologies Engineering, 2017.

[21] Chiaradia D, Xiloyannis M, Antuvan C W, et al. Design and embedded control of a soft elbow exosuit. 2018 IEEE International Conference on Soft Robotics (RoboSoft). IEEE, 2018.

[22] Enoka R M, Duchateau J. Muscle fatigue: what, why and how it influences muscle function. The Journal of physiology, 2008, 586(1): 11-23.

[23] Jaworski Ł, Karpiński R, Dobrowolska A. Biomechanics of the upper limb. Journal of Technology and Exploitation in Mechanical Engineering, 2016, 2(1).

[24] Drillis R, Contini R, Bluestein M. Body segment parameters. New York University, School of Engineering and Science, 1969.