Analysis and Conceptual Design of a Passive Upper Limb Exoskeleton

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***Abstract*—This paper reports a preliminary design of a passive upper limb exoskeleton with 6 degrees of freedom to support workers in industrial environments in a vast range of repetitive tasks. Leveraging the detailed analytical model developed in previous research, the best springs configuration to balance the system during motion is designed through an efficient optimization routine. The model is validated with commercial software for specific overhead tasks, and aspects of the proposed balancer physical implementation are evaluated.**

***Index Terms*—Upper Limb Exoskeleton, Wearable Devices, Design Optimization, Virtual Prototyping, Gravity balancing.**

I. Introduction

Nowadays, manufacturing companies are increasingly introducing automation technologies to comply with the high requests of modern markets. Nevertheless, industrial operators are still involved in many repetitive manual tasks [1]. An ExoSkeleton (ES), namely, an assistive device that can be used to enhance the user's physical capabilities by supporting the body's gravitational load during motion, may offer an effective strategy to reduce the risk of injuries in production lines providing muscle fatigue relief [2]. This research aims to present a conceptual design of an accurate and light, wearable 6 Degrees of Freedom (DoFs) ES capable of keeping a good alignment with the human body and compensating for the gravity loads via passive elements only. The proposed solution is achieved by exploiting the methodology of [3]. To the best of the authors' knowledge, few 6-DoFs passive upper limbs ESs have been designed in academia or industry. In [4], a passive arm support is designed having as main constraints inconspicuousness and wearability. However, this device is not portable, being for people with Duchenne muscular dystrophy.

II. Exoskeleton Design

The system primary purpose is to compensate for gravity loads acting on the human upper limb. The proposed ES showed in Fig. 1 and Fig. 2a is based on 6-DoFs kinematics with 5-DoFs for the shoulder joint (two displacements plus three rotations) and 1-DoF for the elbow. Six main links are connected to form a serial chain with 6R joints, i.e., $R_0,\ R_1,\ R_2,\ R_3,\ R_4,\ R_5$. Gravity compensation is implemented with five passive elastic elements to minimize weight and reduce cost. Similarly to existing commercial ESs [4], [5], elastic bands are used instead of classic linear springs (Fig. 1, green elements). Two 1-DoF balancers [6] and one novel 3-DoFs balancer for the shoulder joint [3], [7] are employed (Fig. 2a, SPRING $1,\ 2,\ 3,\ 3,\ 5$). By defining specific functional requirements (i.e., the user's features and simulated movements), computationally efficient optimization studies may be carried out exploiting the analytical tool and the MATLAB open-source code developed in [3]. So, the optimal coefficients and positions of the springs can be found, thus, maximizing the accuracy of the gravity balancing. Through this theoretical approach each movement within the upper limb workspace may be used. For instance, this paper considers one optimal solution which best fits aspects such as accuracy on the gravity balancing, lightness and wearability.

III. Discussion and Conclusions

Fig. 2a reports the optimal solution obtained by imposing the motion sowed in Fig. 2b (named as *SOLUTION 1*, *OPT. MOV 3*, *HP. NZFL* springs in [3]). SPRING $1,\ 5$ are connected between two consecutive links (gay, blue and light blue links), whereas SPRING $2,\ 3$ are attached to the link $2,\ 3$ center of mass and SPRING 4 to a point on the harm holder, all being fixed to GCS_2. This balancer configuration is chosen after

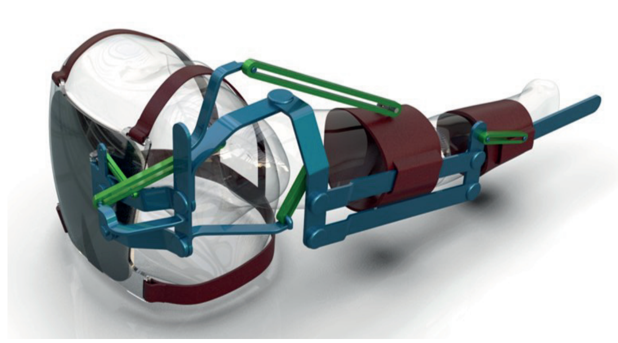

Fig. 1: Passive 6-DoFs upper limb ES CAD model. Five elastic bands (green elements).

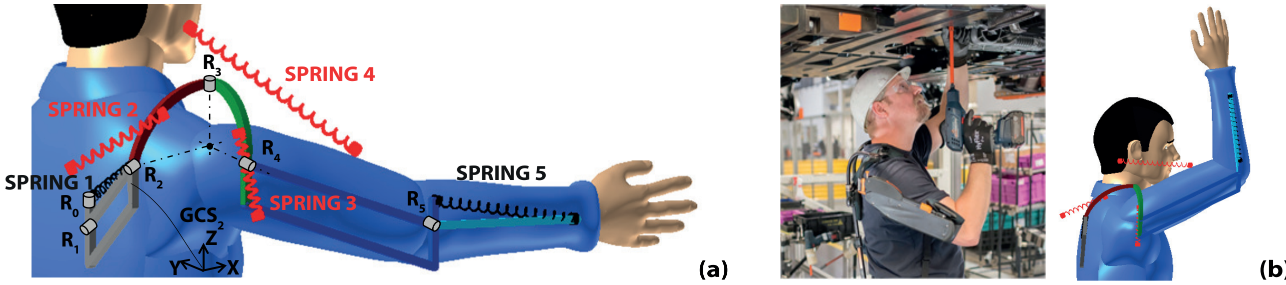

Fig. 2: (**a**) ES parametric model developed in the multi-body software Recurdyn and optimized in MATLAB [3] (initial configuration). (**b**) Typical industrial overhead movement (drilling, final configuration).

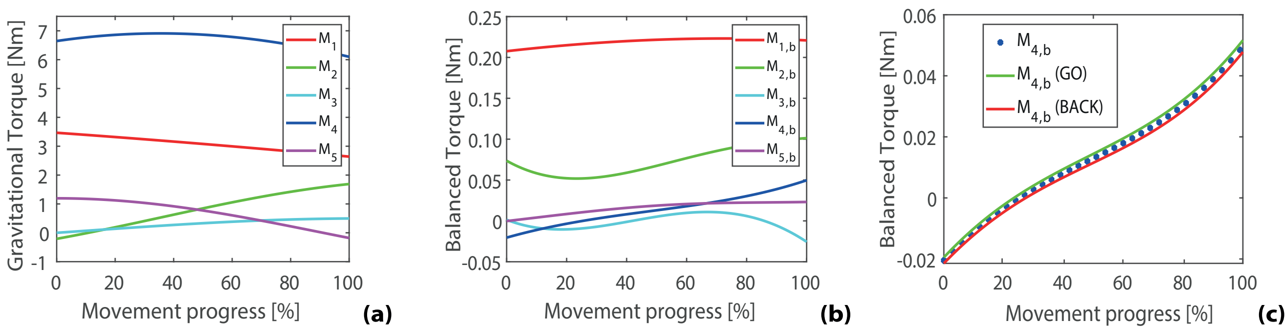

Fig. 3: Reaction torques in each ES R_i joint ($i \in [1, 5]$) during the motion: (**a**) gravity torques M_i, (**b**) balanced torques $M_{i,b}$, (**c**) hysteresis effect on R_4 ($M_{4,b}$ for spring with hp. no damping, $M_{4,b}$ GO and BACK for spring with damping).

comparing the balancing springs type to be used (zero/non-zero free length) [8] and investigating several results by evaluating different 3-DoFs balancer optimal configurations (i.e., arrangement of the elastic elements), the task to be reproduced and the ES material properties. Fig. 3 shows (**a**) the torques due to gravitational load in each ES joint and (**b**) the torques after the spring balancing effect. The ES is fully balanced, obtaining a torque reduction percentage higher than 97.5% for each R joint. Fig. 3c shows the hysteresis effect due to the springs damping: a gap in the balancing occurs between the simulation of the forward (GO) and downward (BACK) motion. Similarly to [4], a damping coefficient has been evaluated so that the hysteresis effect is lower than 10% for each R joint, thus, not significantly influencing the balancing effect. The worst impact occurs in R_4 joint since the SPRING 4 balances most of the weight due to the upper arm. Evaluations on the physical realization of the proposed balancer have been made considering specific criteria, e.g., body interference, workspace, and balancer configuration. Interesting applications to overcome possible collisions between the user and the device during the motion are investigated in [4] and will be considered as further applications. The proposed lightweight simplified assembled ES has been designed via the tool developed in [3]. This parametric, accurate and fast analytical model may be useful during the preliminary design stages. Its versatility permits to easily change the input motion law to reproduce every movement in the ES design space and to customize the geometric and mass parameters according to the user's limb size.

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