Towards Supernumerary Robotic Limbs as Personal Protection Equipment

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***Abstract*—In the last decade, the advent of supernumerary robotic limbs (SRLs) from the research community has shown important benefits in many fields. Based on their design, SRLs can provide workers with additional limbs for augmenting their abilities, e.g. grasping multiple objects simultaneously or helping for balancing in near-ground tasks. In this paper we show as this kind of technology can play an important role in the safety and ergonomic of workers, reducing vibration transmission along the arm and relocating loads on the worker's joints. This may open the way to a new generation of personal protection equipment (PPE).**

***Index Terms*—Supernumerary Robotic Limbs, Vibration Suppression, Ergonomic, Assistance Robotics**

I. Introduction

Since its birth, robotics has been developed to assist and help humans in many of their life duties. Industrial robotics has been one of the main branches of this field, particularly devoted to improving industrial efficiency and employees' work conditions [1]. From a historical point of view, the robotics paradigm moved from the idea of "*dull, dirty, and dangerous* [robots]" to "*human-robot collaboration*" [2]. The latter is allowing for implementing a more complex framework, by integrating the human high cognitive skills with the power and precision of robots [2]. This new trend has introduced also new methods and tools for dealing with safety and ergonomic into the factory environment. Indeed, numerous working tasks, requesting dangerous and detrimental physical demands, may increase the risk for work-related musculoskeletal disorders (WMSD) [3]. In particular, factors like workload, bad postures, and body vibration transmission drastically increase the chance for serious injuries. In 2017, the Italian National Institute for Insurance against Workplace Accidents and Occupational Disease (Istituto Nazionale Assicurazione Infortuni sul Lavoro, INAIL) reported that, in Italy, almost 34500 statement for musculoskeletal disorders, ascribable to working context, have been notified. The robotic research community has proposed different solutions for dealing with these issues, without compromising efficiency. Notable examples are robotic exoskeletons [4], which are generally task-oriented and focused on assisting specific body districts (e.g. low-back, shoulder, elbow). Promising results also come from grounded and mobile systems [5], which can be easily reconfigured for improving worker ergonomic during task execution.

Fig. 1: In picture, a user using the supernumerary robotic arm-hand system for holding a box. Main parts of the system are the gravity compensatory arms (Armor Man 2.0, Tilta) and the soft robotic hand (Pisa/IIT SoftHand [6]), connected by a customized damping wrist.

In the last decade, a new design of wearable robots has been proposed for improving humans abilities and/or helping impaired subjects: Supernumerary Robotic Limbs (SRLs). They consist of additional robotic limbs, designed for acting in cooperation with the user's natural limbs, allowing for tasks that generally request multiple users or external assistance, e.g. holding and interacting with large objects [7].

Here we present a semi-active supernumerary robotic arm-hand (shown in Fig. 1) intended for industrial workers assistance. The design of this new system provides a two-fold benefit: the potentiality of augmenting the worker capacity thanks to the extra limbs, and the prevention of injuries due to overload and vibrations. In this regard, it can be considered as an innovative and advanced personal protective equipment.

A preliminary introduction of this idea was proposed in [8] by the authors. In this paper, in section II the hardware design of the device is described, highlighting its main features. In Sec. III, general considerations and discussion on the use of the system are reported. Finally, Sec. IV concludes this paper.

II. Hardware design

As shown in Fig. 2, the system is composed of two main sub-parts: the gravity compensatory arms attached to the

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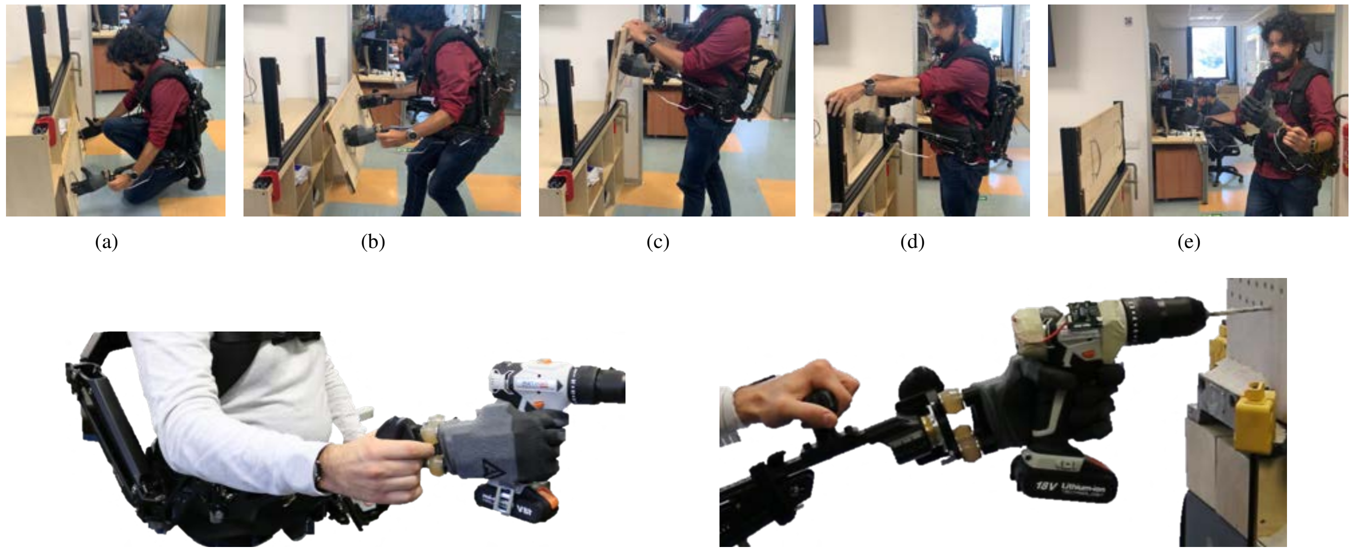

(a) (b) (c) (d) (e)

(f) (g)

Fig. 2: Pictures (a)-(e) show a subject holding-and-interacting with a large object by using the supernumerary robotic arm-hand system. In particular, we can see the subject approaching the object (a), lifting it (b), easily holding (c), interacting for fixing (d) and releasing (e). Picture (f) and (g) show a subject using a drill with the supernumerary system for dissipating vibrations, thanks to the custom damping wrist.

wearable vest and the soft robotic hands connected to the compensatory arms trough a custom damping wrist.

A. Gravity compensatory arms

With the aim of maintaining a low level of complexity for controlling the whole system, a passive solution has been selected for implementing the additional limbs. In particular, the wearable steady-cam Armor Man 2.0 (Tilta) has been adapted and integrated with two robotic hands. It consists of two 6 degrees-of-freedom spring-actuated gravity compensatory arms ($2kg$ each) fixed on a central aluminum plate of a wearable vest ($3kg$), covered by polyurethane padding. They allow the user for comfortably holding (see Figs. 2(a)-(e)) loads up to $22kg$.

B. End-Effector

In order to avoid overloading the worker's hand and wrist joints, we have equipped the extra limbs with the SoftHand, an under-actuated soft robotic hand [6]. In this way, the load can be relocated from the worker's arms to his/her torso and legs, which are anatomically bigger and stronger. Although this is the only active part of the system, its control is extremely simplified by the intelligent mechanical design. A specific finger joint mechanism [6] allows different grasps by commanding the same closure pose using a single motor. According to the soft robotic concept [9], the finger joints can adapt to the different shapes and sizes of the grasped object without compromising the contact stability. The robotic hand closure can be proportionally commanded with a handle fixed on the wrist interface.

As stated in Sec. I, this system has been specifically designed for reducing injury risk related to joint overload and hand-arm vibration transmission. For dealing with this last issue, we proposed a custom damping wrist interface (see Figs. 2(f) and 2(g)) for connecting the robotic hand to the gravity compensatory arms. The design process started from theoretical analysis on a simplified 1-DOF mass-spring-damper model [8], according to the EU directive (2002/44/EC) and the ISO 5349 guidelines. Based on the theoretical results and the physical constraints of the device (e.g. encumbrance and weight), a comprehensive review on the commercially available solutions of dampers has been conducted. After preliminary test with some of them, a final prototype has been implemented as shown in Fig. 2. As shown in figure 2(g), four gel-based dampers have been connected in parallel between the robotic hand and an aluminum prosthetic-like wrist, which allow pronation/supination rotation.

III. General considerations

Although primarily intended for augmenting user abilities, the design of the supernumerary robotic limbs intrinsically proposes a high potential for improving safety and ergonomic. This is the case of the system here presented, which permits the wearer to autonomously and easily hold and manage large and heavy objects, avoiding overloading his/her natural arm joints. This is an interesting advantage for for industrial applications like manual material handling, large and heavy parts assembling, and heavy tool manipulation. The presence of an anthropomorphic soft robotic hand makes the system high versatile thanks to the ability to perform a firm grasp, and the need to act in environments and with objects designed for human use. It is worth noting that the load assistance can be provided also by many robotic exoskeletons. However, to the best of our knowledge, they generally limit their load assistance up to the elbow joint, leaving the hand and wrist structures still overloaded. With the system proposed, thanks to the additional robotic hand we can re-locate any load from the user's arm (including hand and fingers) to the torso and legs, reducing in this way the risks of injuries and augmenting the comfort and the global ergonomic.

Another important aspect of the proposed system is related to the ability of dissipating vibrations when using vibrating tools (e.g. drill, polisher, saw). This helps for reducing the risk for hand-arm vibration syndromes (HAVSs). These syndromes consist of pathological conditions due to the vibration transmitted to the arm from many working tools [10]. The specific design of the presented custom damping wrist, in combination with the soft robotic hand, allows the worker of manipulating this kind of tools safely reducing the risk for HAVS.

According to the points above discussed, we may consider these new robotic devices as a novel generation of PPE. Many other advantages can be introduced thanks to the presence of extra limbs. For example, in future works we will investigate a new design of the proposed system, increasing the active parts. This would allow introducing more autonomy on the robotic side, which can autonomously and quickly intervene in a dangerous situation, e.g. for moving away or protecting from falling objects. A more active version would also open to more complex and accurate cooperation and interaction between the user and the robotic system.

IV. Conclusion

In this paper, a supernumerary robotic arm-hand system is proposed for augmenting workers' ability and improving safety and ergonomic. In particular, the system permits for relocating the load from small and weak joints, like the hand and wrist, to less vulnerable (e.g. torso and legs). In addition, the integration of a soft robotic hand with a custom damping wrist prevents the worker from vibration-related injuries.

Future works will be oriented for improving the comfort and mechanical design of the system, implementing a locking joints system. In addition, a deep investigation of the efficacy of vibration suppression of the system with different vibrating working tools will be conducted.

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