Summary

The thesis aims to describe a new passive upper-limb exoskeleton for industrial application. These devices can improve the workers' comfort and productivity by reducing muscle activity and intra-articular compressive force during overhead work. Passive industrial exoskeletons presented in literature or commercially available typically employ a spring-based mechanism to balance the gravitational torque acting on the shoulder. As an alternative, the exoskeleton described in this thesis aims to exploit the elastic characteristics of artificial pneumatic muscles (PAMs). The latter have several features that make their use within the exoskeleton structure fascinating: their intrinsic deformability and similarity to the skeletal muscles allow a safe human-exoskeleton interaction; in addition, PAMs have a high power-to-weight ratio and are easy to install, so they do not increase the bulkiness and the weight of the system; finally, the availability of PAMs with different sizes, characteristics, and load capabilities, as well as the possibility to regulate the internal pressure, allow for extensive customization of the actuator's response that can match several applications and working conditions. The final device shall also ensure an upper limb range of movement appropriate to its intended use, human-exoskeleton interaction forces less than the limits of safety and comfort, and a set of size regulations that allow adjusting the exoskeleton to fit users with different physical characteristics.

After a brief introduction to the physiological and biomechanical aspects of the shoulder joint and an overview of the state of the art of upper limbs industrial exoskeletons (Chapter 1), the thesis describes the design process of a PAMs-based exoskeleton prototype. Chapter 2 presents the mathematical model used to identify the type of PAM and the motion transmission that minimizes the mismatch between the gravitational torque acting on the shoulder and the support torque provided by the exoskeleton in a workspace suitable for most work tasks. Then, the kinematic chain design that allows the flexion-extension and abduction-adduction of the arm is described in Chapter 3, and the effect of the possible misalignment between the exoskeleton and shoulder joint centers on the performance of the exoskeleton is discussed. In Chapter 4, the exoskeleton architecture is presented, together with the results of the analytical model used for the human-exoskeleton interaction forces estimation and the finite element static analysis. Analytical and numerical analyses demonstrated the exoskeleton feasibility and led to the development of a prototype of about 5.5 kg suitable for users with a height between 160 cm and 175 cm. Finally, the prototype is validated by bench tests (Chapter 5) and experimental laboratory tests involving voluntary subjects to perform static and dynamic tasks (Chapter 6). Validation tests showed that the exoskeleton can adequately support the user during overhead tasks. A shoulder muscle activity reduction of up to 75% has been detected, while there is no evident increase in lumbar muscle activity due to the transfer of loads by the exoskeleton.

Moreover, subjects did not declare discomfort due to excessive pressure applied by the exoskeleton on the user’s body.