2011 IEEE International Conference on Robotics and Automation
Shanghai International Conference Center
May 9-13, 2011, Shanghai, China

Body Extender: whole body exoskeleton for human power augmentation

Simone Marcheschi, Fabio Salsedo, Marco Fontana and Massimo Bergamasco

Abstract—**The PERCRO laboratory of Scuola Superiore Sant'Anna has recently completed the development and functional assessment of the Body Extender (BE) system, an advanced wearable robot expressly conceived for augmenting the human strength for handling of heavy materials in unstructured environment. The system is composed by four robotic limbs with anthropomorphic kinematics and has a total of 22 independently actuated degrees of freedom. The leg locomotion and the force servo-amplification allow operations in environments that are hardly accessible by the conventional handling systems preserving the force sensibility during the manipulative tasks. Possible applications are handling of military materials in narrow spaces, rescuing of victims in natural and human provoked disasters and handling of heavy parts in the manufacturing of large products. The paper reports the system specifications taken as a reference for the design, the criteria and verification methods, the architectural solutions used for the implementation of mechanics, electronic and control components and the results of the preliminary experimental assessment.**

I. INTRODUCTION AND BACKGROUND

Exoskeletons for Human Performance Augmentation (EHPA) belong to a special class of wearable robotic systems that are conceived for augmenting human strength capabilities. The main characteristic of this kind of devices is that the human operator "wears" the robot and controls the movements of the robot by moving his limbs in a natural way. EHPA are generally intended for applications in the field of assistive device for elder people or disables, in the military field and in applications where handling of heavy materials in unstructured and narrow environments are required.

Early ideas of EHPA have been proposed around the end of the 18th century, but the first concrete attempt to develop such kind of device has been initiated by General Electric in 1966 that in 1971 completed the development of a hydraulic powered whole body exoskeleton called "Hardiman" [1]. The system, composed by an internal lightweight sensorized exoskeleton and an external powered exoskeleton, was designed for handling maximum payload of the order of 750 pounds. While quite successfully results were achieved in the control of only the arms, limitation on the computing power of the electronics available at that time prevented the possibility to fully demonstrate the capability of the system.

About in the same period, Prof. Vukrobratovic independently developed an exoskeleton composed by two under-actuated legs, intended for supporting disabled/elderly people during their daily life activities, achieving some promising results [2]. In the early 80's Prof. Kazerooni initiated systematic studies on robotic extenders specifically intended for material handling, addressing the problem of the control of their interaction with the human and the environment [3,4]. Kazerooni with his team developed and successfully test different hydraulically and electrically powered non-isomorphic robotic arms and legs.

Fig. 1. Picture of the PERCRO BE worn by a user.

In 2000 the American Defense Advanced Research Project Agency (DARPA) launched the EHPA strategic project, aiming at the development of advanced exoskeletons for increasing the physical performance of ground soldiers, to enhance their survivability and mission capabilities [5]. The project involved a large number of American universities and companies with different roles and

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This work was supported in part by the Italian Ministry of Defense under National Research Project PRN 266 and by the European Community in the framework of the TESBE experiment of ECHORD project.

All the authors are from PERCRO Lab of Scuola Superiore S. Anna, Pisa, Italy (www.percro.org).

Massimo Bergamasco acts as contact author (phone: + 39 050 883786; fax: +39- 050- 883333; e-mail: massimo.bergamasco@sssup.it).

978-1-61284-380-3/11/$26.00 ©2011 IEEE

competencies. The first tangible result of project was the BLEEX system (Berkley Lower Extremity EXsoskleton), a self powered hydraulic leg exoskeleton developed by the research team of Prof. Kazerooni and unveiled in 2004 [6]. The system, composed by two exoskeletons for the legs having each 7 DoFs of which only 4 actuated (hip abduction-adduction, hip flexion, knee and ankle flexion), is intended for aiding ground soldiers in the transportation of heavy equipments located in the backpack. The tracking of the user's movement is achieved using only internal sensors (encoders and accelerometers) without the need for sensors located at the interface with the operator (e.g. force sensors). On year later, the team of Jacobsen, also involved in the EHPA project, developed a similar device using rotary hydraulic motor instead of traditional linear hydraulic actuators [7]. At the end of the EHPA program, Jacobsen has extended its exoskeleton adding two actuated arms equipped with passive hangs to lift payloads. In the second phase of the DARPA project, the Biomechanics Group at MIT has developed an exoskeleton for the leg using quasi-passive joints relying solely on the energy stored by suitable activated springs, with the aim to drastically reduce the power requirements of the system, while at the meantime to provide a sensible reduction of the metabolic cost of payload transportation [8].

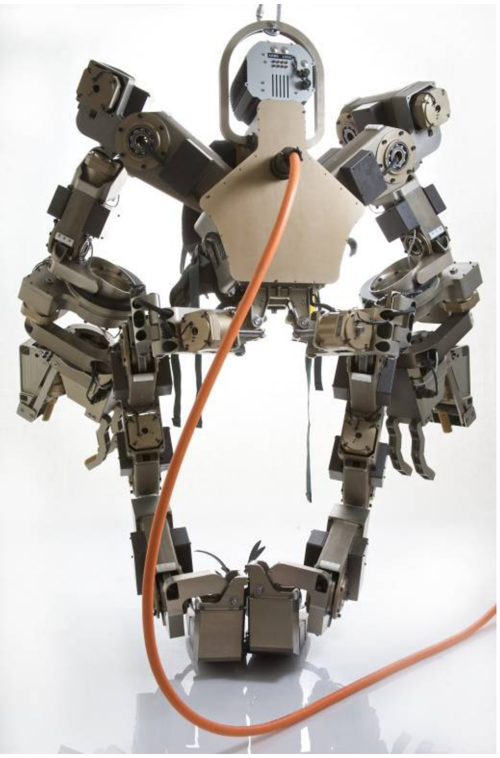

Fig. 2. Rear view of the PERCRO BE.

Another relevant research result, carried out independently from the EHPA project, is the Hybrid Assistive Limb (HAL) developed by Prof. Sankay. In the latest version (HAL 5) the system is a full bodied under-actuated exoskeleton powered by a reduced set of electrical motors (only 2 for each limb for a total of 8 actuators) intended for both augmenting and assistive purposes [9]. The capture of the motion intention of the user is achieved through the elaboration of the EMG signals produced by his/her muscles. The system requires about two months for optimal calibration due to sensible differences from subject to subject in the location and value of the electrical potentials.

The HULC exoskeleton developed by Berkley Bionics, a spin-off company of the research group of Prof. Kazerooni, is a highly under-actuated exoskeleton for the legs (only one actuator per leg, located in correspondence of the knee) featuring very impressive speed performances and load capacity.

In the recent years, a rising interest of the robotic research community on this kind of devices has led a large number of research groups in the world to undertake similar works. However, the researches have been progressively oriented to applications that can be addressed by highly under-actuated devices, such as the assistance for the elderly or the disabled or the carrying of heavy loads during walking. On the contrary, the handling of heavy material in unstructured environment requires the possibility to perform the grasping of objects, having very different geometries, and to move them along general trajectories. Considering that the grasping cannot be performed directly by the operators hands because in general high grasping forces are required and that, for similar reason, the reaction forces required for generating the movement of the object have to be transferred by the exoskeleton directly to the ground, it is evident that a whole body exoskeleton intended for material handling should have a complete set of DoF for each limb (6 DoF) and also a complete set of independent actuators. Relating to this last point it is worth to note that, in general, the torque requirements at each joint are relatively high if compared with the torque that can be exerted by the corresponding physiological joint of the operator and that, for this reason, it is not viable to exclude any actuator. The conclusion is that body extenders intended for this application are likely to be relatively bulky and complex devices, posing non trivial problems to the development of the controller that have to show satisfactory tracking performances and ensure at the same time the stability of the physical interaction of the extender with environment and the human operator.

Addressing the full problem of the force augmentation for the general handling of materials, in 2004 PERCRO laboratory of Scuola Superiore S. Anna started the development of a fully actuated whole Body Extender (BE) that has been successfully demonstrated in March 2009. This prototype is one of the few working example of full body exoskeleton having such a large set of independent actuators.

II. DESIGN GUIDELINES

Considering the envisaged applications for the BE, it has been set as the ideal objective for its design the achievement of a device that could be immediately used also by subjects not previously trained. In other terms, the use of the system should not require the substantial modification of the normal motor habit and strategies that humans usually adopt while handling materials. This system requirement lead to the definition of a set of design guidelines that are explained in detail in [10] and can be briefly summarized as follows:

- Correspondence between the workspace of human limbs and the one of the robotic limbs: limitations of the natural workspace of the limbs forces the operator to modify its usual motor strategies;
- Adherence of the encumbrance of the mechanical structure to that of the human limbs: when operating in tight spaces, excessive encumbrance of the mechanics could require substantial modification of the motor strategies in order to avoid the occurring of interferences with the surrounding environment;
- Correspondence between the human's and BE's equilibrium conditions: a mass distribution of of the device components not similar to that of the human body can induce the user to change his/her natural body posture and movements to prevent the overturning of the system under the action of gravity;
- Minimization of the resistance forces: to achieve the tracking of his/her body motions, the user has to apply forces/torques to the device in correspondence of the 5 interfaces (feet, hands and trunk), even if no load is handled. An excessive value of these resistance forces could require some kind of compensations to be performed by the user and, hence, a modification in his/her motor habit.

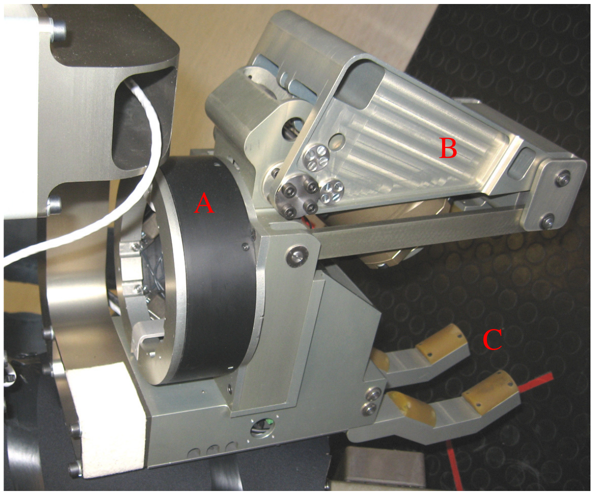

Fig.3. The gripper of the PERCRO's body extender: force sensor connected to the handle integrated in the gripper (A), moving jaw (B) and fixes jaws (C).

The identification of these requirements have given a clear criterion for selecting the best implementations during the preliminary design phase of the device. For example, an isomorphic kinematics (described in section IV) has been selected and also innovative actuators (described in section VI) have been designed. The verification of the above described design requirements has gone through a set of experimental tests and dynamic simulations discussed in [10].

III. SYSTEM OVERVIEW

The PERCRO's BE is a wearable robotic device expressly conceived for material handling in unstructured environment. The main system functionalities are the tracking of the operator limb movements and the amplification of the forces applied by the user. In Table I, the main specifications of the system are reported.

TABLE I
SYSTEM SPECIFICATIONS OF THE PERCRO'S BODY EXTENDER

Feature	Value
DOF of each robotic arm + gripper	4 + 1
DOF of each robotic leg	6
Rated load capacity of each robotic arm	500 N
Rated grasping force of the gripper	1700 N
Rated angular speed of the robotic joints	60 deg/s
Range of the amplification	3 – 20
Total weight of the robotic device	160Kg

The robotic structure is composed by 4 robotic limbs (2 arms and 2 legs) connected to a central body (the backpack). The robotic limbs have kinematics isomorphic to that of the corresponding limbs of the operator. The device has a total of 22 degrees of freedom, each of them independently actuated by mean of a DC brushed torque motor.

Each robotic arm is equipped with a gripper (Fig. 3) having one servo-amplified degree of freedom. The grasping of the objects is achieved by the translation of one jaw with respect to two fixed jaws. The grasping force is proportional to the pressure applied by the index and middle finger over the trigger integrated in the handle grasped by the user.

The sensory equipment of the device consists of 22 incremental encoders integral to the rotors of the electric motors, 5 six-components force/torque sensors mounted in correspondence of the 5 connecting points between the user and the device (hands, feet and trunk), 2 one-component force sensors integrated inside the gripper for measuring the force applied by the user on the trigger and 1 three-axis accelerometer integral with the backpack for estimating the direction of gravity vector respect to the system.

To keep at minimum the total weight of the device, the structural parts have been primarily realized in hard anodized high strength aluminum alloy (Ergal). The computations required for the control of the device is distributed on a central unit and 16 local units, located along the robotic limbs and communicating with the central unit through a high speed field bus. The electric power is supplied to the device by an external power supply system consisting of 13 batteries connected in series (for a total output nominal voltage of 78 Volts) and a dedicated battery charger that continuously recharges the batteries, being permanently connected to the main electrical network. The power supply system is able to ensure the continuous work of the device for over 8 hours, in case of absence of energy from the main electrical network.

IV. KINEMATICS

In order to reduce the complexity of the device, the kinematics of each limb has been derived from the simplified kinematics of the correspondent human limb, eliminating those DOFs that make redundant the mobility of the limb and have relatively small range of motion (rotation of the shoulder and of the ankle), as depicted in Fig. 4. The axes of the remaining joints are substantially aligned with the corresponding axes of the physiological articulation, i.e. the kinematics of the robotic limbs is substantially isomorphic to the one of the corresponding human limb. The opening and closing movement of the gripper has been implemented by mean of a parallelogram mechanism which allows the translation of the moving jaw respect to the fixed ones.

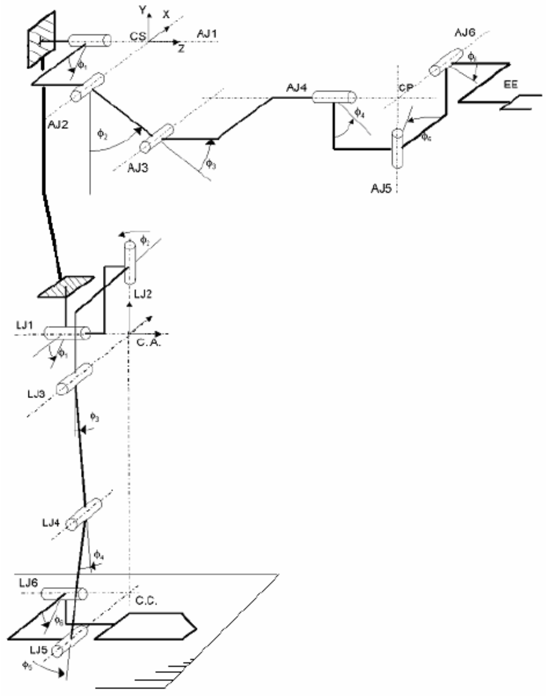

Fig. 4 Scheme of the kinematics of one arm and one leg of the PERCRO BE.

V. ACTUATION SYSTEM

A. Linear actuator

All the DOFs of the BE, except for the forearm prono-supination, are driven by mean of the same linear actuator expressly designed for the system. The linear actuator is composed by an electric motor, an incremental encoder, a high precision ball screw and two angular contact ball bearings. The electric motor is a commercial frameless DC torque motor composed by rare earth permanent magnets and brushes in graphite. This component is able to exert a peak torque of 7Nm and a maximum continuous torque of 6Nm, with an external diameter of 80mm, a length of 60mm and a weight of 1,4Kg. The ball screw has a pitch of 4mm, a mechanical efficiency of 90% and a negligible backlash. The linear actuator is able to exert a maximum force of about 8000N, with a total weight of 2,4Kg.

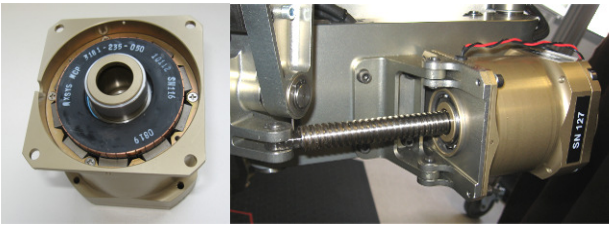

Fig. 5. Pictures of the actuator group disassembled (on the left) and coupled with the screwball (on the right).

B. Actuation Module

For the joints having relatively low requirements in terms of range of motion and torque capability, the conversion of the linear movement generated by the linear actuator into the rotation of the joint is achieved by mean of a simple lever mechanism acting directly on the link to be actuated. For the joints having larger range of motion and torque requirements, the motion conversion is achieved by mean of an innovative mechanism, composed by a pantograph, two metallic tendons and an output pulley connected with the link to be actuated (Fig. 6). All of these components are integrated in a modular group, named actuation module, which includes also the linear actuator and the case (see [11] for more details on the actuation module). This modular component has been designed in two different sizes (size A and size B) and it is used for driving all the transversal joints (joint axis orthogonal to the link length direction) of the legs (Fig. 7) and of the arms. The size A has a range of motion of 110 degrees and exerts a maximum continuous torque of about 500Nm, while the size B has a range of motion of 90 degrees and exerts about 270Nm. The total reduction ratios (between the motor shaft and the joint) are 102 for size A and 58 for size B. The total weight of size A is about 6Kg, while size B weights 5Kg. The experimental tests carried on size A have shown a mechanical efficiency of about 85% and a maximum stiffness of 25000Nm/rad at the output pulley.

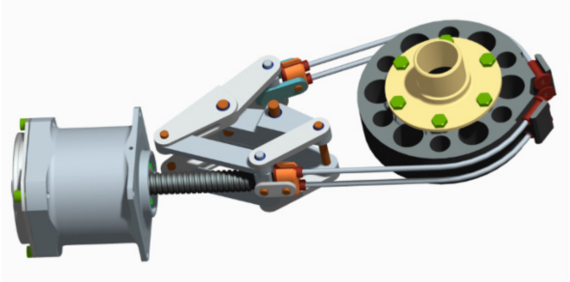

Fig. 6. CAD view of the internal components of the actuation module.

Fig. 7. Three transversal joints integrated for the implementation of the PERCRO BE right leg.

VI. OVERVIEW ON THE ELECTRONIC COMPONENT

The architectural scheme of the BE electronics, showing the main units is reported in Fig. 8. The main units are the following:

- The Power Supply Unit, which supplies the current required by all the control units and by all the motor current drivers;
- The Central Control Unit, located behind the user's head and in charge of managing the global state of the system. It computes the velocity and compensating torque targets for the local motor controllers and communicates with the Local Unit by mean of a high performance field bus arranged on 4 lines, one per each robotic limb;
- The Local Control Units, which computes the command voltage references for the motor current drivers (starting from the targets received from the Central Unit), acquire all the sensors signals and communicates with the Central Unit by the field bus.
- The Robotic Structure divided in 5 main components: legs, arms and trunk. Each of them is connected to the user body through a 6 DoF force sensor. The arms are connected through a handle shaped force sensors to the user's hands. The leg is connected under the foot and a fifth connection is with the trunk, behind the user back.

This distributed solution based on EtherCAT field bus communication has been used to dramatically reduce the wiring complexity, increasing the reliability of the system, and also to reduce the communication latency.

VII. PRELIMINARY EXPERIMENTAL ASSESSMENT

Preliminary tests have been carried out on the fully integrated system to assess the tracking (with and without load) and the grasping/lifting/handling (up to the rated load) capabilities of the device. The tests performed for assessing the body movement tracking capability, with the feet fixed on the soil and the BE unloaded, have evidenced maximum resistance forces of the order of 30 N, that are well tolerated by the user. These tests have also evidenced a good mass distribution of the device, producing equilibrium conditions coherent to those of human body and, hence, allowing the user to keep his/her natural postures.

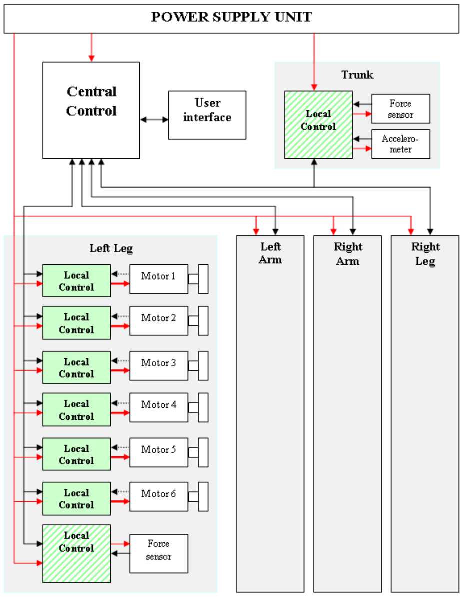

Fig. 8. Schematization of the electronic architecture of the BE.

However there are limitations on the maximum attainable joint velocities and excessive resistant forces arising during the tracking of the feet movements that make the walking phase somewhat unnatural. Indeed, due to the join velocity limitation, the user is forced to walk at a speed lower than natural and, consequently, to displace in the lateral direction more than in the natural conditions the center of gravity of the system, to ensure its balance when only one foot is on the soil.

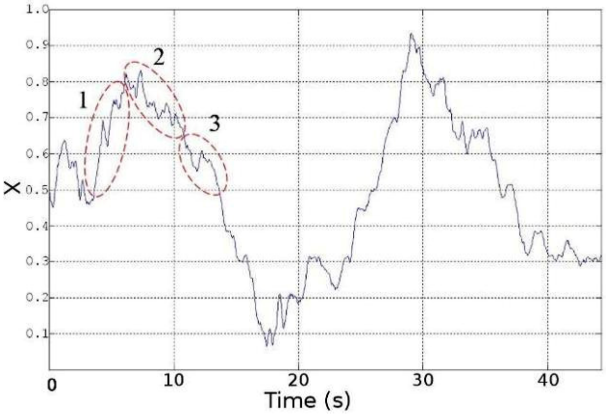

Fig. 9. Factor of weight repartition on the leg estimated during three steps (1 = the weight is completely supported by the right leg):The weight of the device is transferred on the right leg while both foot are on the ground (phase 1); the step is performed (phase 2); the left foot is leaned on the ground and the system weight is progressively transferred on both the legs (phase 3). A complete step is performed in about 6 second.

This is due to the reduction of the inertial forces that normally occur during walking, forcing the user to proceed into successive quasi-static equilibrium points (Fig. 9).

The tests performed to assess the grasping and lifting capabilities have shown the compliance of the device to the specified rated load. Moreover, the user can perceive the external forces exerted on the environment with sufficient accuracy (according to the set force amplification ratio).

However, the tests have also evidenced important criticality for the user to ensure the equilibrium of the system during the handling of objects having weights close to the rated load (500 N). This is due to the considerable displacement of the system Zero Moment Point produced by the weight of those objects, whose value is, indeed, comparable to that of the system (Fig. 10).

To ensure the equilibrium of the system the user has to change considerably his posture and, hence, that of the BE in order to make the ZMP of the system fall inside the support polygon. This is a very challenging task for the user, because, from one hand, he is not aware of the real equilibrium conditions of the system, since, due the amplification of the BE, he feels only a fraction of the load and, from the other hand, he should change his posture to an extent that his own equilibrium condition would not allow (i.e. the user would fall). This latter problem has been preliminary solved by exerting a supporting force on the trunk of the user. But more generally, a new collaborative control of the posture should be investigated. The knowledge of BE equilibrium conditions should be combined with the motion intention of the operator to produce the resulting commanded posture. In other terms the operator's intended motion should be modified in order to fulfill the constraints required to ensure the equilibrium of the system. Furthermore it could be investigated the possibility to make the operator more intuitively aware of the equilibrium conditions, controlling the BE to generate suitable artificial haptic cues on the operator body.

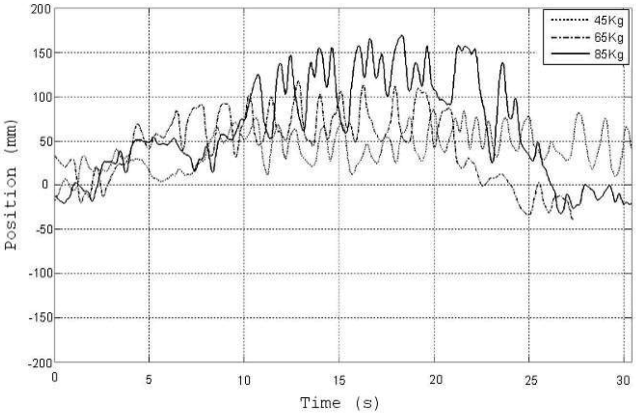

Fig. 10. Estimated ZMP of the device while three different loads are raised.

VIII. CONCLUSION

A fully actuated body extender able to amplify the force of a human operator called PERCRO Body Extender has been designed, realized and preliminary tested. The whole design process has been oriented to the final objective of achieving a device having a high degree of transparency and flexibility, despite the relatively large mass and inertia mainly due to the high number of actuated joints. To this aim four design criteria to be satisfied for all the components of the system have been set as reference for their development.

The experimental assessment of the system has confirmed the soundness of the design criteria, even if it has also evidenced the need for better control strategies in order to reduce the resistant forces arising during the tracking of the body movements, as well as the need for communicate some artificial feedback to the user to make him aware of the real equilibrium conditions of the system, during the handling of objects, having weights close to the rated load of the device.

ACKNOWLEDGMENT

This work is partially funded by the Italian Ministry of Defense, in the framework of the national plan for the military research, and by the European Community in the framework of the TESBE experiment of ECHORD project.

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