Mechanical Design and Experimental Characterization of a Novel Hand Exoskeleton

Marco Fontana, Massimo Bergamasco, Fabio Salsedo

PERCRO Laboratory, Scuola Superiore Sant'Anna,Pisa, Italy
E-mail: *m.fontana@sssup.it, m.bergamasco@sssup.it, f.salsedo@sssup.it*

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SUMMARY. Exoskeletric robotic interfaces have been employed in several fields of Human Robotics research like in rehabilitation, haptic interaction, teleoperation and space applications. In this paper a novel Hand Exoskeleton (HE) is presented. Such device is optimized for haptic interaction with virtual environment and allows exerting high accuracy controlled forces on the fingertip of the index and thumb of the operator. Several design solutions are conceived and implemented for optimizing the accuracy and mechanical performances. The use of Remote Centers of Motion mechanisms allows achieving compactness and lightweight. Moreover an improved stiffness of the transmission and reduced requirements for the electromechanical actuators have been achieved thanks to a novel Patent Pending principle for integrating speed reduction ratio within the transmission system. The mechanical design and some preliminary characterization tests for this device are shown.

1 INTRODUCTION

An Exoskeletric Haptic Interface (EHI) is a haptic device whose mechanical structure is located in proximity of the part of the body that is interested in the interaction. The kinematics of such devices is often designed in a way that the linkages of the structure follows the movements of the human operator. EHIs have attracted a lot of attention among the haptic research community since they show several advantages. Their most relevant feature is the optimal workspace matching between the human reachable workspace and the haptic device workspace. Moreover, EHIs perfectly fit the application where reduced visual and spatial encumbrance is needed.

Hand Exoskeletons (HE) belongs to the family of EHI. Their functionality is to exert controlled forces on the human fingers. HE can be classified in two functional sub-categories depending on the capability of exerting forces on one phalanx only (the fingertip) or on multiple phalanxes.

- Mutli-Phalanx Hand Exoskeletons (MPHE) are devices able to exert different forces on more than one of the phalanxes of the same finger; commonly the force can be applied on a fixed direction normal to the phalanx axis and belonging to the medial plane of the finger.
- Single-Phalanx Hand Exoskeletons (SPHE): are able to exert forces on the distal phalanx only; some devices are able to generate a force only along a fixed direction but more commonly they can exert forces along any wanted direction.

HE can be further distinguished in two other categories:

- Anthropomorphic Device: when the kinematic of the HE is morphologically equivalent to the kinematic of the fingers;
- Non-anthropomorphic: when the kinematic of the HE is morphologically different from the finger kinematic scheme.

In the scientific literature of the last 30 years there are many works reporting the design of different HEs. The first example of HE was introduced by Zarudiansky back in 1981 [1]. The inventor has registered a patent on a telemanipulation system equipped with a master device able to provide force feedback on different phalanxes of the human hand. At JPL laboratory, in 1988, Jau [2] built a complete teleoperated master/slave arm comprehending a hand exoskeleton device for four fingers. In the same years Burdea develops a pneumatic actuated hand force feedback device [3] able to exert a single force on the distal phalanx along a direction that is assigned by the kinematic of the device and the position of the finger.

Few years later, Bergamasco [4] et al., at PERCRO Laboratory, developed another four fingers MPHE able to exert forces on each phalanx of each finger. A non-anthropomorphic device was realized by Koyama from Keio University. The device is a three finger exoskeleton with passive clutches actuation [5]; the device that is anchored on the wrist of the user and it is able to exert forces in every direction belonging to the sagittal plane of the fingers. Frisoli in [6] developed another non-anthropomorphic HE called Pure Form Hand-Exos for VR applications.

Nakagawara [7] built a anthropomorphic device integrating the concept of encountered haptics in the field of exoskeletons. The device is a HE with just 1 DoF for each finger and it is able to track the finger of the user without any contact (even at the fingertip) through a non contact sensor placed in correspondence of the nail. When the contact takes place in the remote environment a plate is moved against the user fingertip.

In this paper we describe the mechanical design of a high performance portable SPHE able to exert forces on the index and thumb fingers in the range of few Newtons but with exceptional capabilities of accuracy and resolution. The target of application of the HE that is described in this paper is the haptic interaction in virtual environment or in tele-manipulation systems. The reference tasks are the precision grasping between index and thumb, the manipulation and the exploration of surfaces and objects involving forces in the range of 0-5N.

The realized device is shown in Figure 1. The design work aimed at the realization of a high performance device able to render light forces in an accurate way.

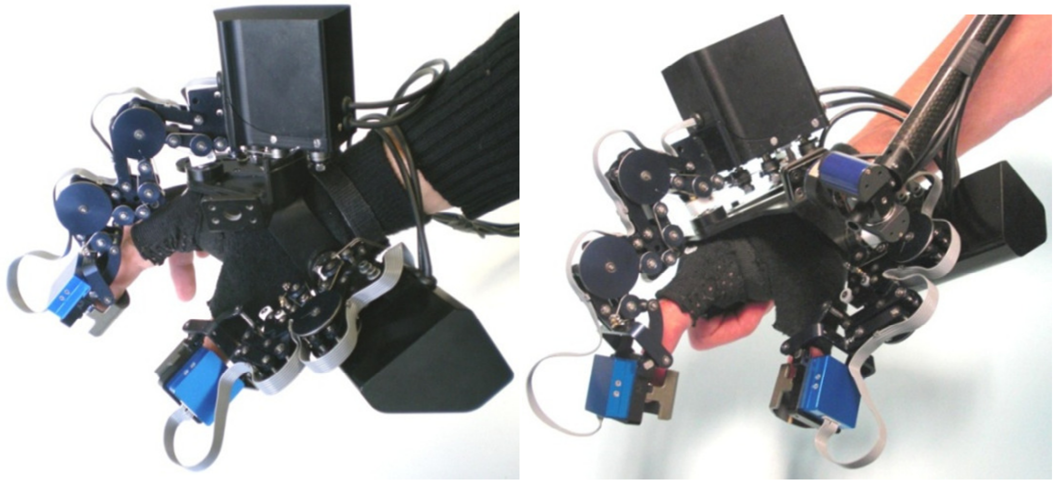

Figure 1: Picture of the realized HE without (left) and with (right) tracking system

2 KINEMATICS, TRANSMISSION AND ACTUATION

The kinematic scheme that has been adopted for the developed HE can be defined as a *quasi-anthropomorphic* kinematics. The choice was driven by the fact that anthropomorphic kinematics presents many positive features that well fit the requirements of a portable haptic devices:

- Highest matching ratio between workspace of the mechanism and required workspace
- Short path for the robotic linkages
- Wearability with limited visual encumbrance

In our design, we adopt a kinematics that is morphologically identical to finger kinematics but it slightly differs for the length of the links. The perfect coincidence would be desirable but it is not allowed because when the flexion joints of the finger are extended the kinematics falls in a singularity. The concept of *quasi-anthropomorphic* kinematics is represented in Figure 2-left. The finger kinematic model that has been taken as reference is the one adopted by Springer in [8]. Such model considers both the index and thumb finger as 4 DoFs 4R manipulator.

A simplification has been assumed for reducing the needed number of actuators. The actuation of 4 DoFs would require the use of 4 actuators and, since the actuators generally constitute the heaviest fraction of the mechanical assembly of an HI, we introduce a simplification that allows the use of only 3 motors. The rotation between the distal and middle phalanx (joint j_{H4}) has been coupled with the rotation between the middle and the proximal phalanx (joint j_{H3}). This coupling reflects the behaviour of the human finger and in particular it has been assumed that the rotation of the joint j_{F4} is equal to the rotation of the joint j_{F3}.

An accurate description and analysis of such of the kinematics implementation can be found in [9]. In brief, the peculiarity of this design is the use of Remote Center of Motion for the implementation of the flexion joints of the kinematics of Figure 2-right. This allows achieving compactness and lightweight of the mechanical components. Moreover a smart (patented) solution for the cable transmission further improves the global weight and stiffness of the device through the realization of an intrinsic speed reduction ratio.

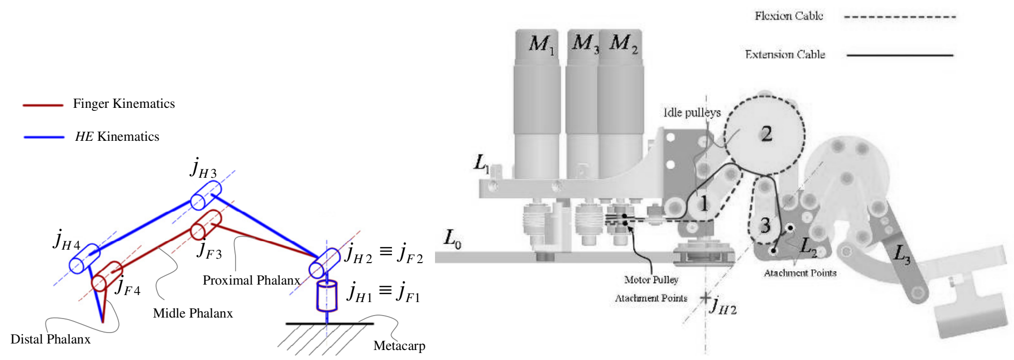

Figure 2: Scheme of the kinematics of the HE (left) and scheme of the transmission routing for the joint j_{H2} (right)

The obtained device is able to exert 5 Newtons of force on each fingertip with a global weight of 1.1 Kilos. In Table I the main mechanical performances are summarized.

TABLE I
MAIN MECHANICAL PERFORMANCES

Symbol	Quantity	Value
DoF	Degrees of Freedom for each finger	3
F_{max}	Maximum continuous force	5N
W	Weight of the whole device	1.1 kg
w_a	Weight of one finger mechanism	0.51 kg
B_w	Mechanical Bandwidth (expected)	25 Hz

3 FORCE SENSING

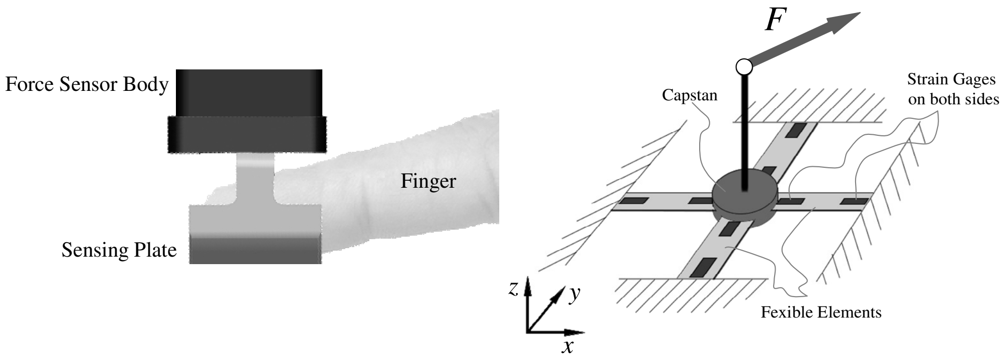

Figure 3: Scheme of the positioning of the force sensor (left) and scheme of the *Maltese Cross* force sensor (right)

A further action for improving the force accuracy has been done designing and realizing two integrated 3 DoF force sensors to be included at the end-tip of the each finger exoskeleton. These sensors are used for the compensation of the residual friction and inertia forces to improve the performances of the novel device. Each sensor is placed on the last link of the HE. The spring of the sensor was located on the dorsal side of the fingertip (see Figure 3-left) and the input (or sensing plate) plate, i.e. the plate where the force is sensed, is hold through a portal like structure (Sensing Plate) under the fingertip. The conditioning electronics is placed directly in proximity force sensor for limiting the path of the weak signal cables (see Figure 4).

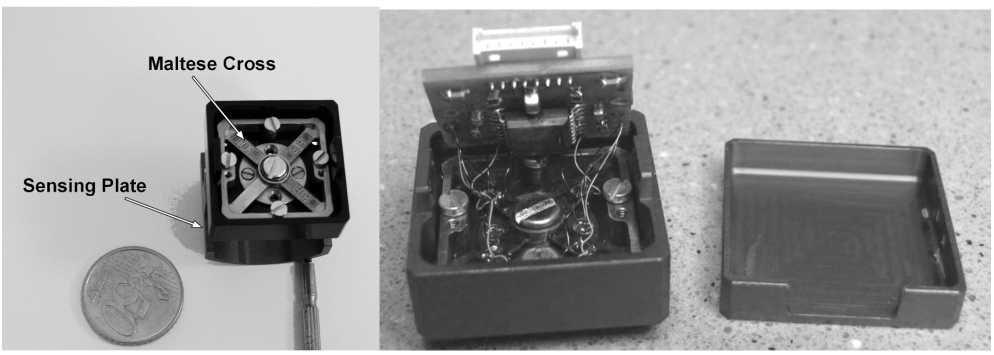

Figure 4: Picture of a prototype of the force sensor

The architecture of the spring element of this sensor exploits the well known *Maltese-Cross* flexible structure represented in Figure 3-right. This was chosen because its spatial encumbrance is very limited and particularly well distributed for the application. This spring is composed by four beams disposed to form a cross. The beams converge in a central plate (capstan) where the forces are applied. The strain gages are placed on both the sides of the beams close to their ends. A complete strain gages bridge is used for each beam.

The force sensor characteristics were experimentally measured as follows:

- Sensibility: 0.18-0.53 V/N
- Sensitivity to torques: very high, torques has to be avoided
- Maximum force range: --5.5N/+5.5N
- Repeatability: 0.08N
- Resolution (limited by the noise): 0.9mN

4 ELECTRONICS

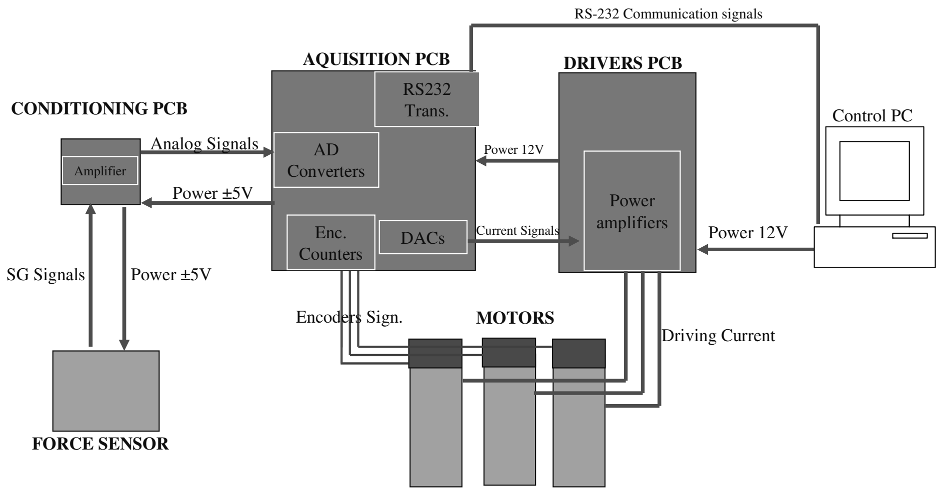

Figure 5: Architecture of the whole electronic layout

When dealing with portable devices and when high precision force sensing is required, the design of the electronic components has to be carefully treated. The cabling of the motors, acquisition of position and force sensor must be compatible with portability and the noise issues have to be carefully treated. For this reason the HE was equipped with a custom electronics for the conditioning of force signal, acquisition of sensors and current driving of the motors.

The adopted architecture for the electronics is shown in Figure 5 and functionality can be summarized as follows:

- Conditioning: Amplifying the signals of the force sensor before AD conversion;
- Acquisition: AD conversion and communication of 4 signals from the force sensor at a resolution of 16 Bits and counts the 3 impulse encoders from the 3 encoders of the actuators and DA conversion of the driving current signals commanded by the controller;

- Driving: Providing a voltage-driven current driver of 3 channel for the control of the motor torque
- Data exchange: Serial port communication with the control PC.

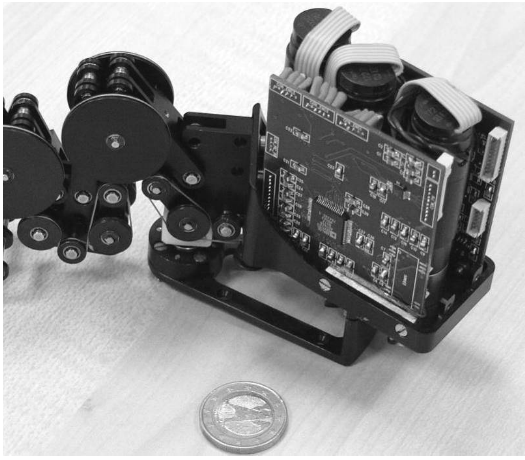

Figure 6: Picture of the final PCBs integrated in the mechanics

The whole electronics components were located on board and integrated into the mechanical design of the device like represented in Figure 6 obtaining optimal conditions for the noise and simplifying the cabling with the remote Control PC.

In order to integrate the electronic system into the HE, a layout was studied and the functionalities were shared on 3 different boards:

- A Conditioning electronics PCB integrated in the force sensor box;
- An Acquisition and communication PCB integrated in the motor box;
- Driver electronics integrated in the motors area.

A special care has been taken for minimizing the noise on the analogue signals:

- Linear motor driver for reducing the electromagnetic noise
- Grounding and power scheme optimized for limiting the cross talking between the different grounding reference

5 VERIFY AND CHARACTERIZATION

5.1 *Electrical Noise*

The noise on the force signal is a critical issue for the effectiveness of certain control strategies. The noise that affects the force sensor that is included in the control loop as a force reference signal. A test has been performed acquiring the sensor signal and collecting the data for the estimation of the average noise on the force signal under these conditions:

- no load was applied in the force sensor;
- the motors were powered;
- the hand exoskeleton was fixed on an isolated support free of mechanical vibrations.

The average noise resulted:

$N_{\sigma} = 0.6[mV]$

A peak to peak noise of about

$N_{p-p} = 2.2\ [mV]$

5.2 *Maximum force and Stiffness*

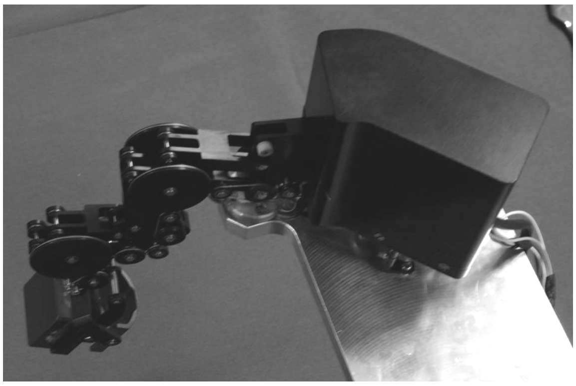

Figure 7: Picture of the experimental setup for the evaluation of performances of the HE

In order to estimate the stiffness of the HE a measure has been done in the most critical position. The experimental platform that was used can be seen in Figure 7. The Index HE was mounted on a rigid plate that was solidly connected to ground. The end-effector was fixed through a spherical joint in correspondence of the sensible point of the force sensor.

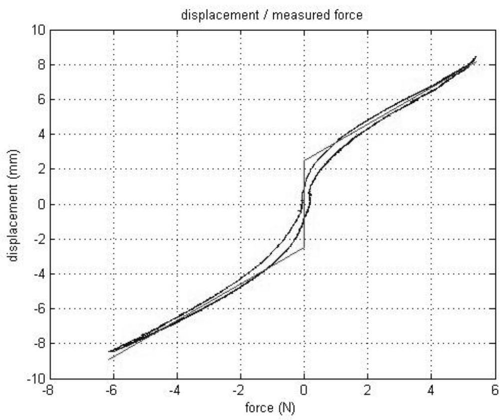

Figure 8: Experimental data of the displacement versus the force at the end-effector of the HE

The force was then increased up to the maximum (+5N) and lowered back to the minimum (-5N). The force was applied in a quasi static way and the load cycle period was 40 seconds. The rotation of the encoder and the force measured at the end-effector were recorded for several cycles. In Figure 8 the curve that result from the measurement is shown. As can be observed a central area of very low stiffness can be detected. The hypothesis is that some of the bearing of the structure are not effectively transmitting the forces due to the backlash. When the load is applied the backlash is cancelled and all the mechanical structure is loaded in the proper way. The stiffness far from the zero load condition is calculated through a minimum square fitting:

$$K_{HE} = 1\left[\frac{N}{mm} \right]$$

5.3 *Mechanical Characterization*

For the purpose of the complete characterization of the mechanical performances of the designed device, an experimental identification of the model parameters has been carried out. The aim of such identification is to provide the mechanical dynamic properties of the device in the worst condition of compliance and maximum inertia in order to have a lower bond of the bandwidth of the controller that will be developed in future.

Usually for the parameter identification some sensors are added to the plant in order to have a better estimation of the velocities and the accelerations. Accelerometers can be placed on the output of the system like in [10] and [11] or additional force sensor can be introduced for a better estimation of the input force like in [12].

When only encoders at the motor axis and force sensor at the end-effector are available the velocity and accelerations are estimated through a linearization and integration of the digital signal from the encoders. This generally brings to a noisy and inaccurate estimation of the velocity especially for the higher frequencies. However, that the aim of this preliminary tests is just to have a rough estimation of the mechanical parameter. For this reason it was considered sufficient the results that are obtained with the on board sensorization.

Moreover, the HE is generally a MIMO system that has to be characterized by a 3 by 3 matrix of transfer function, but the aim of this identification is not to provide an accurate dynamic behaviour of the whole system. This would require a more accurate analysis and probably the use of a additional sensorization systems. Here the author reports the mono dimensional characterization of the HE in a condition that is considered the worst position and the worst direction in the workspace with respect to the output bandwidth response. This is done to provide a lower bond of the bandwidth giving the possibility to design an explicit force control algorithm.

The position that is more critical for the high compliance and the high mass seen from the user is the extended position (when the flexion joint of the user finger are all extended). The direction of maximum compliance is the normal direction to the flexion plane of the finger.

The characterization was done providing to the joint-1 a chirp signal of fixed amplitude in a frequency range of 0-120Hz. Different amplitude of were used in order to verify the linearity of the system. The second and third DoFs were kept fixed by a constant force against the end stop of the extension movement. The transfer function:

$$G_{uLo} = \frac{\theta_{1m}}{\tau_{1m}}$$

where:

- θ_{1m} is the angular displacement of the first motor joint ;
- τ_{1m} is the torque on the first joint;

has been characterized experimentally. The obtained bode plot is represented in Figure 9-left and the correspondet anti-resonant and resonant frequencies are:

$$f_{ar} \cong 23Hz$$
$$f_r \cong 29Hz$$

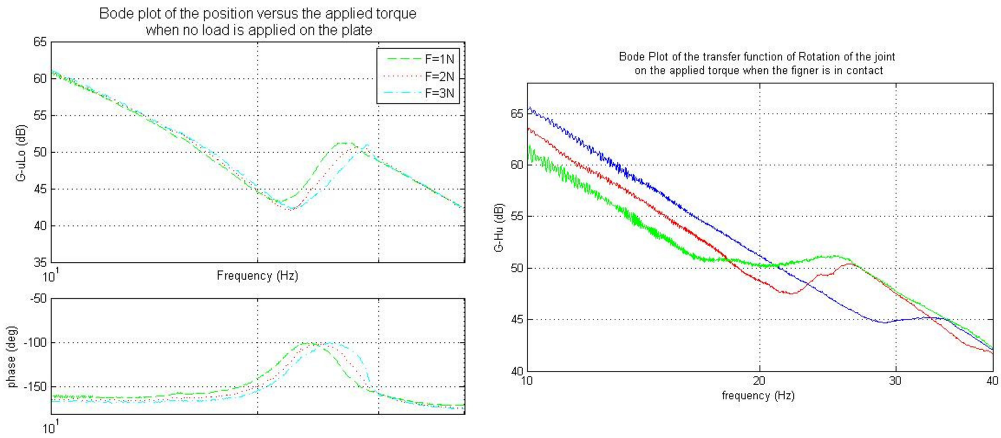

Figure 9: Bode plot of the transfer function G_{uLo} .(left) and magnitude Bode plot of the joint rotation on the applied joint torque when the three different human finger are in contact with the end-effector (right)

The model can be schematized with a 2-mass model analogous to the model describe when the human impedance is null. The corresponding data expressed at the end-effector are:

$$\mathrm{M_m} = 0.29[kg], \quad \mathrm{M_g} = 0.15[kg], \quad C_\mathrm{m} = 7.72\left[\mathrm{Ns}/\mathrm{m}\right], \; C_\mathrm{g} = 1.1578\left[\mathrm{Ns}/\mathrm{m}\right]$$

An analogous Bode plot and very close resonant and anti-resonant frequencies were found for the thumb finger device. The same tests were done with the index finger in contact with the plate exerting a constant normal force of 2N with 5 different subjects that were asked to try to keep the finger in a fixed position in the stiffest way they can. Figure 9-right shows the magnitude Bode plot of the obtained data. It can be observed that the human load does not introduce major changes in the resonant and anti-resonant frequencies respect to the unloaded condition of Figure 9-right. This means that the human impedance is neglectable respect to the haptic device impedance and has not any major affect on the position versus force transfer function. The correspondent resonant and anti-resonant frequencies are estimated in the range:

$$f_{ar} \cong 18 \div 23Hz$$
$$f_r \cong 25 \div 35Hz$$

6 CONCLUSIONS

In this paper we have described the work that has been done for conceiving and designing a novel portable haptic device. The design tents to maximize the accuracy of the device reducing the unwanted friction and inertia forces.

The main introduced novelties are:

- A quasi-anthropomorphic kinematics for SPHE with a novel Patented transmission system for the actuation a RCM ;
- A novel method for coupling the rotation of two links of a serial mechanism using the crossed parallelogram mechanism, avoiding the use of toothed wheels;
- The integration of the whole acquisition, sensing and driving electronics in the structure of the exoskeleton;
- A custom force sensor that is purposely designed for the application

The result consists of a lightweight device with a global weight of approximately 1 kilogram. The force resolution of the custom force sensor together with the low friction force transmission system are very promising for achieving a very good force accuracy and resolution. A lower boundary of the bandwidth has been measured and shows values that are promising for the implementation of an explicit force controller.

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