

# A Bio-Inspired Haptic Interface for Tele-Robotics Applications

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**Abstract**—This paper presents the design concept for a bio-inspired exoskeleton intended for applications in tele-robotics and virtual reality. We based the development on an attentive analysis of the human arm anatomy with the intent to synthesize a system that will be able to interface with the human limb in a natural way. Our main goal is to develop a multi contact-point haptic interface that does not restrict the arm mobility and therefore increases the operational workspace. We propose a simplified kinematic model of the human arm using a notation coming from the robotics field. To figure out the best kinematic architecture we employed real movement data, measured from a human subject, and integrated them with the kinematic model of the exoskeleton. This allows us to test the system before its construction and to formalize specific requirements. We also implemented and tested a first passive version of the shoulder joint.

**Index Terms**—Exoskeleton, Haptic Interface, Teleoperation, Bio-Inspired Device, Biorobotics

## I. INTRODUCTION

This work presents a design approach to synthesize the kinematics structure of a new type of bio-inspired exoskeleton, that is intended to be used as haptic control interface to teleoperate a remote robot. Our main goal is to develop a wearable system with increased workspace and with the capability to deliver a multi-point force feedback to the user's arm.

The primary goal of teleoperation is to enable the human operator to see and feel the remote environment, besides that he also should be able to identify himself with the target robot [1]. Therefore, exoskeletons do not only act as input, but also as haptic feedback devices to provide the human operator a broad sensory experience.

A challenge in controlling an exoskeleton as a *bidirectional mechanical transducer* [2] is to reach a balance between *stability* and *transparency* [3]. Criteria for the quality of haptic feedback are defined in [2]; comparative empirical studies for different kinds of haptic feedback and for different haptic devices are provided in [4] and [5] respectively. One category to distinguish between different constructions of exoskeletons is their *degree of activity*: on the one hand pure passive devices were developed, e.g. [6] or [7, ZJUESA]. On the other hand empowering exoskeletons were built up, see [8]. Between these extrema one finds exoskeletons acting as force-reflecting controlling devices.

These can be further subdivided into solutions that are fixed to an external basis (grounded) [9], [10] or [11, MAHI] and those remaining wearable (ungrounded). The latter is reached by the ESA exoskeleton [12] and by the study described in [13].

Another crucial part of developing an exoskeleton is the design of a proper actuation system. While the systems presented in [10], [12] and [14] are driven by cables that bring forces from the motors (located in the base) to the joints, the authors in [15] use a pneumatic system to actuate directly the moving parts of the exoskeleton.

A further comparison of existing exoskeletons under the criteria of physical properties, ranges of motion and joint torques can be found in [16]. The wearable exoskeleton we are developing will feature the following properties: an unrestricted and tracked shoulder movement, a hybrid hydraulic-pneumatic actuation, and a novel bio-inspired control system.

In the following section we introduce the model of the human kinematics we used during the design process. Section III deals with the kinematic model of the exoskeleton, in particular we only report on the system that is supposed to be coupled with the shoulder of the user. Section IV deals with control in a teleoperation scenario and proposes a possible bio-inspired control system for a single exoskeleton joint. In section V we introduce the design for the exoskeleton and present some preliminary results. Finally section VI draws out the conclusions and the future developments.

## II. HUMAN ARM STUDY AND KINEMATIC MODEL

Starting from the sternum, which has been chosen as a reference basis, and moving towards the distal part of the limb, one can find the following bones: clavicle, scapula, humerus, radius and ulna (see Figure 1).

In literature, one finds different kinematic models for the human arm [17], each one oriented to describe certain aspects rather than the others. We decided to represent the kinematic model of the human arm using a notation coming from the robotics field in order to couple it more easily with the kinematic model of the exoskeleton. Of course, we introduced numerous simplifications and assumed the articulations like joints with a well defined geometry. Nevertheless, we think that for our study this is sufficient.

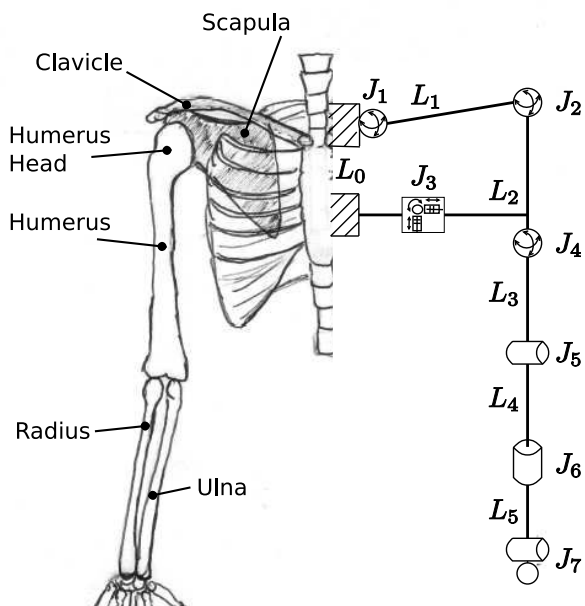


Fig. 1. Representation of the skeleton of the human arm and its simplified kinematics model using robotics notation:  $J$  stands for “joint”,  $L$  for “link”.

The model we formalized is shown on the right hand side of Figure 1: Again, we can separate the kinematic architecture in two different parts: shoulder and arm kinematics. The shoulder kinematics is composed of four joints, three spherical (3DOF) and one planar. More precisely the planar joint can be decomposed into one rotational and two prismatic joints, however, in this first representation we preferred to use a compact notation. It also should be noted that the shoulder kinematics can be further divided in two other parts: one that is a closed kinematic chain, and the other that is an open kinematic chain represented by a spherical joint located in the proximal part of the upper arm link. The closed chain is formed by three links and three joints: the spherical joint  $J_1$  is located between  $L_0$  (the link with the inertia reference system) and  $L_1$ . The spherical joint  $J_2$  is located between  $L_1$  and  $L_2$ . Finally the planar joint  $J_3$  connects the base link  $L_0$  and  $L_2$ .

The first consideration we can do on this kinematic chain is about the overall mobility. The three joints have a total of 9DOF, but because of the parallel nature some constraints limit the mobility. We define  $\mathbf{q}$  as the configuration variable, this is a vector with  $m$  components ( $\mathbf{q} \in \mathbb{R}^m$ ) that unambiguously defines the position and the orientation of all the rigid bodies that compose the kinematic chain. In this case we only consider minimal configurations; this means that it is not possible to define the system with less than  $m$  scalars unambiguously.

Given the kinematic chain we can calculate the dimension for  $\mathbf{q}$  applying the Kutzbach-Grübler formula for spatial mechanisms [18]:

$$m = 6(n - j - 1) + \sum_{i=1}^j f_i. \quad (1)$$

Where  $n$  is the number of links present in the kinematic chain,  $j$  is the number of joints, and  $f_i$  is the number of degrees of freedom for the  $i^{\text{th}}$  joint. If we apply this equation to our specific case we obtain:

$$m = 6(3 - 3 - 1) + \sum_{i=1}^3 f_i = -6 + 9 = 3. \quad (2)$$

This means that this chain has overall three degrees of freedom, therefore to define unambiguously its kinematic configuration we only need to define three scalars. Which joint variables do we have to choose to define the configuration of the shoulder? In theory it is possible to choose just three variables from the nine we have. In practice we will see that there are some choices that are better than others, especially if we need to measure these quantities in a real system.

Starting from the joint  $J_4$  the human arm can be represented as an open kinematic chain. As we can see from Figure 1, joint  $J_4$  (lower part of the shoulder) connects link  $L_2$  to link  $L_3$ . This joint has a total of three DOF and allows movements of extension-flexion, adduction-abduction and rotation around the upper arm axis.

Moving towards the distal part of this model we encounter joint  $J_5$  (the elbow) that connects link  $L_3$  with link  $L_4$ , this is a one-DOF rotational joint that allows forearm flexion and extension. Finally, we have joint  $J_6$  (first degrees of freedom for the wrist) that connects link  $L_4$  with link  $L_5$ . In comparison with the human arm anatomy this represents a simplification. Indeed in human beings it is a complex movement of both radio and ulna bones that allow the wrist rotation. Anyhow in a first approximation this simplification is not so critical for our purposes. A more accurate model will be formalized in case the results obtained are worse than the minimum expectations.

In Figure 1 we also represented the other joint for the wrist, joint  $J_7$ . This has a total of two DOF, which in the human arm allows the wrist flexion-extension and adduction-abduction. At the moment the hand kinematics is not considered in our study.

### III. THE EXOSKELETON KINEMATICS

The exoskeleton kinematics is strongly influenced both by the human arm anatomy and the goals we want to reach. The central idea is to try to restrict the mobility of the user’s arm as little as possible when he is wearing the exoskeleton. It is also necessary to keep in mind the main requirements for the overall system: lightweight construction, a system that is easily wearable, a multi-contact point haptic feedback, a modular design and a biologically inspired joint controller. All these goals are important to synthesize the kinematic structure for the exoskeleton, but for this initial analysis, the

overall mobility constraints and the necessity to have multi-contact point haptic interface represent the most relevant aims.

If we want to reduce the user's mobility limitations due to the exoskeleton, we can define the following kinematic requirements:

- The upper arm coupled with the upper part of the exoskeleton should have a total of 3 DOF.
- The forearm coupled with the lower part of the exoskeleton should have a total of 2 DOF.

In order to provide the user a broad haptic feedback, our exoskeleton will transmit forces and torques via multiple contact points. One of these points was defined by locating the exoskeleton-shoulder on the user-shoulder, the other will be located in the middle of the user upper arm, and the last one in the middle of the user forearm. These locations are optimal in the sense that they reduce the interference with the human articulation during the user movements. The three different contact-points are depicted in Figure 2.

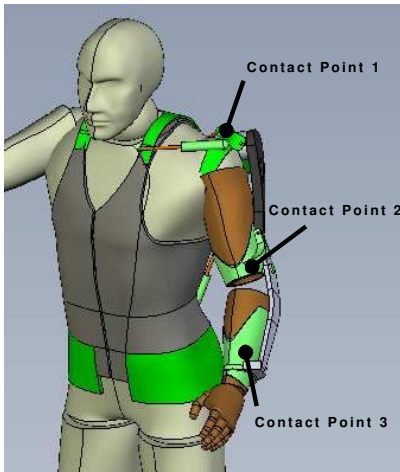


Fig. 2. Contact points between the exoskeleton and the human arm.

#### A. Coupling the Exoskeleton with the Human Arm

It is also important to consider about the overall kinematics that we obtain by combining the arm with the exoskeleton. This will also help us to define how many degrees of freedoms are required for the exoskeleton.

In the next section we will only concentrate on the exoskeleton kinematics that deal with the shoulder and the upper arm of the user, even if we have already started to extend the analysis also for the forearm.

1) *The Upper Shoulder Joint:* In this paragraph the term “upper shoulder joint” denotes the entire kinematic structure of the exoskeleton system that complies with the motions of the human upper shoulder, formed by the clavicle-scapula articulation. Figure 3 depicts the closed chain of the human upper shoulder together with a possible exoskeleton configuration (blue part)

How many degrees of freedom should the exoskeleton configuration, the upper shoulder joint have? From the motion analysis on the human arm it comes up that the upper shoulder has an effective DOF of three. Therefore, we introduced a simplification, such that the closed loop of the upper shoulder is substituted by a single joint with 3DOF. The simplified system is depicted in Figure 7.

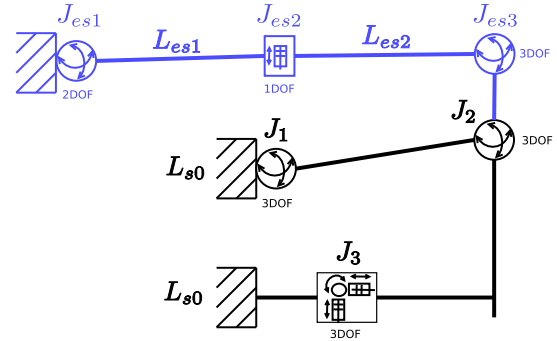


Fig. 3. Closed kinematic chain formed between the exoskeleton shoulder joint and the upper shoulder kinematic chain.

The overall mobility of the simplified configuration can be calculated again with Equation 1:

$$m = 6(n - j - 1) + \sum_{i=1}^j f_i = 6(5 - 5 - 1) + 9 = 3. \quad (3)$$

As shown in Figure 3 the exoskeleton has a total of 6DOF; because we need to actuate a 3DOF kinematic chain, it means that only 3 of the 6DOF have to be actuated and sensed. From a mechanical point of view it is more advantageous to actuate the joints ( $J_{es1}$  and  $J_{es2}$ ) that are located nearer to the barycenter of the body: this way the actuation system is not charged to move also the weight of the actuators itself.

2) *Model Simulations:* To define some specifications for the actuation system of the exoskeleton we built a model using the toolbox SimMechanics in Matlab-Simulink environment. The system is composed of a spherical joint and a prismatic joint (Figure 4).

In order to analyze the motion in a realistic way, we constrained the point  $P$  to lie on a trajectory that we obtained from the motion tracking of the human arm performing an extension-flexion movement of the shoulder.

Once we are sure that point  $P$  is well constrained we can monitor the position of each joint of the exoskeleton in order to evaluate the range of its movement. This is very useful to obtain specifications for the design of the real system.

In the evaluation for a single person the following exemplary data were obtained: the linear position of the prismatic joint changed in the range of about 8cm. The ranges of the Euler angles of the spherical joint were sized about  $30^\circ$ ,  $50^\circ$  and  $15^\circ$  for roll, the pitch and yaw, respectively.

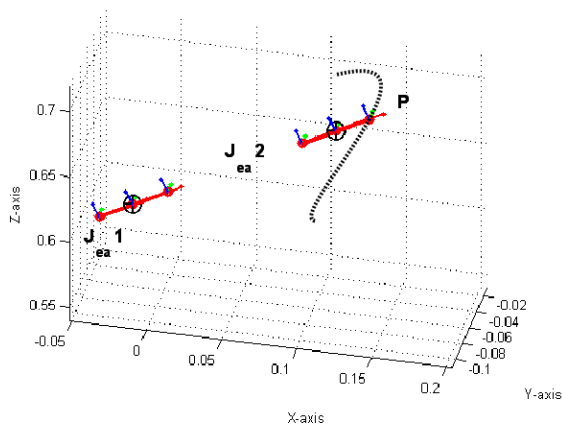


Fig. 4. Simulation for the Shoulder Joint, distances in meters.

#### IV. THE CONTROL SYSTEM AND THE BIO-INSPIRED JOINT

##### A. Control in Teleoperation

Figure 5 depicts the different loops that occur in an application of an exoskeleton in *teleoperation*. For a survey of that field see [19]. The Figure shows the exoskeleton acting as a mechanical transducer between the human operator and the teleoperated robotic system. In addition to the control of the exoskeleton and the robot, we will introduce a central mapping control that determines the art of looping between exoskeleton and robot. However, in this paper we initially focus on the development of control techniques for single units (see the next section IV-B) and solely point out some challenges for the development of the mapping control briefly:

- In general, the exoskeleton and the respective teleoperated robot possess different kinematic structures. Hence the mapping control needs to be able to map spaces of different dimensions smoothly (in terms of human sensation).
- The need to find a suitable trade-off between the conflicting goals of transparency and stability, see [20].
- The capability to control certain slave movements as direct as possible (e.g. the end-effector), while “hiding” other (null-space) movements from the user.
- The need to solve complex inverse kinematics problems in real time precisely.

##### B. The Bioinspired Joint Control

Because we need to keep the system as light as possible, we are developing a hybrid hydraulic-pneumatic actuation system. In the concept we propose (Figure 6), the idea is to include an elastic and damping element in series with the hydraulic actuator in order to be able to change its physical properties in real time. This function can be accomplished, for example, by using a pneumatic spring and modulating the pressure inside the element using proportional valves.

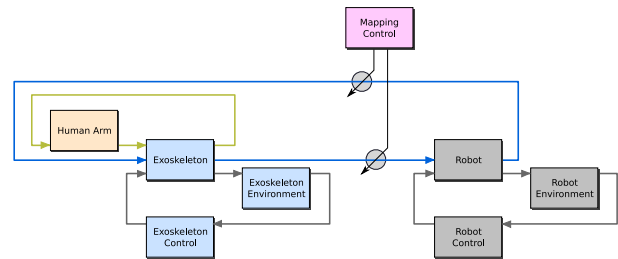


Fig. 5. Exoskeleton used as a Control Device in Teleoperation

The system we are going to control is inherently nonlinear, because of following reasons:

- The presence of a nonlinear pneumatic spring component in the actuation system;
- The nonlinearity of the hydraulic system itself;
- The interaction with an unpredictable system, the human body.

Classical control theory cannot be suitable in this case, we therefore need to explore also other control paradigms [21], [22]. One of them comes, for example, from the physiological study of the human peripheral nervous system, in particular the part of the nervous system in charge of the sensory-motor coordination.

In the human body the stiffness of the musculoskeletal system can be finely controlled using the co-contraction muscle mechanism, by regulating the activity of the gamma motoneurons. Furthermore, there is also a protection mechanism that is monitoring the activity of the Golgi-Tendon organs that are located in series with the muscle and measure the force that this apply on the bone. When unexpected dangerous external load is acting on the muscle, this mechanism acts rapidly in order to decrease the muscle stiffness and let the articulation move under the load. This action has the function to prevent permanent damages to the muscles or the tendon tissues.

The architecture of Figure 6 represents a first trial to mimic this human control. It is characterized by two loops, each with a certain kind of  $\alpha$ -motoneurons [23] (in nature there is no such differentiation): one controls the actuator position and the other represents the protection mechanism above described.

The first loop starts from the neuron that “computes” (upper part of the schema in Figure 6) the difference between the reference position signal and the real position ( $\theta - \bar{\theta}$ ) measured from the hydraulic actuator. The output of this neuron goes to excite the two  $\alpha$ -motoneurons that in turn go to control, by the valves, the pressure of the two actuator’s chambers. This will act on the actuator in order to decrease the discrepancy between the reference and the real position. These two motoneurons have also a cross-inhibition mechanism that it is necessary to govern properly the actuation system, and prevents that the pressure inside the two chambers increase too much. The second  $\alpha$ -loop

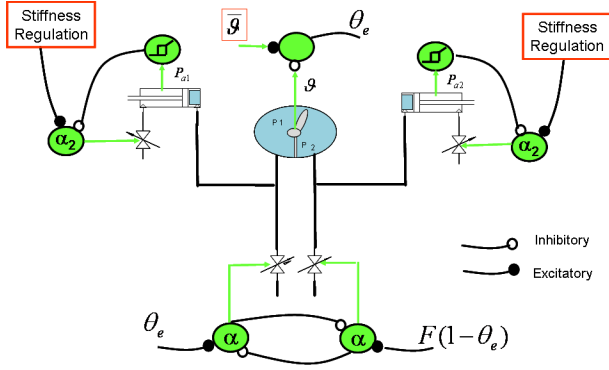


Fig. 6. A bioinspired control schema for position and stiffness control of the single joint actuator

acts on the two pneumatic springs; we have one control loop for each of them. The measurement of the force is in this case exciting a neuron that starts its activation (firing) only when the force is overcoming a certain threshold. The output of this neuron goes to inhibit the  $\alpha_2$ -motoneuron that is responsible for the stiffness control. The neuron has also another input, that in this case is excitatory and it is coming from an high level controller. When we increase or decrease this signal, the stiffness of the two pneumatic springs, and therefore the stiffness of the entire joint, will increase or decrease consequently.

## V. SYNTHESIS OF THE EXOSKELETON KINEMATICS AND DESIGN

In this section we present the kinematic architecture for the part of the exoskeleton that will be connected with the user's upper shoulder.

The mechanical structure is composed of four joints: a sequence of two rotational, one prismatic and one spherical joints. Figure 7 depicts the first concept, which features two connection structures: one that is fixed to the user's pelvis (the belt), and the other one that is connected with the top side of the user's shoulder. In future we will firstly employ rigid materials for these two parts in order to establish stable connections with the human body, secondly we will shape these parts such that they become more comfortable for the user.

The following parameters will also be taken into account in the design process of the device:

- The distance between the exoskeleton and the user's back: if the exoskeleton is too near to the user's back, collisions may occur during the user's shoulder movements.
- The proportions of the exoskeleton – in particular the length of the link between DOF 2 and DOF 4 (see Figure 8) – should be adjustable in order to fit with different user sizes.
- The proportions of the fixations to the user's body – in particular the connection to the shoulder – should also be adjustable: A possible solution could be the usage

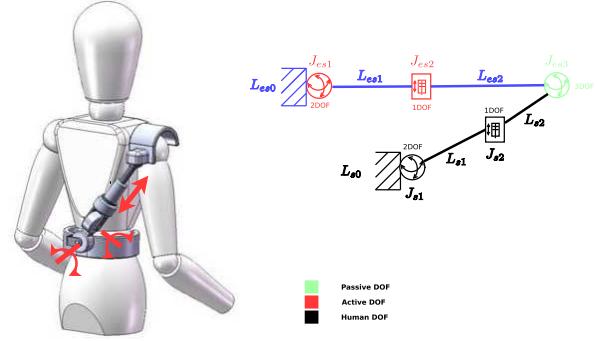


Fig. 7. The Upper-Shoulder joint Exoskeleton concept and its kinematic structure

of an inflatable device, even if this will decrease the stability of the contact point.

To transfer forces and torques to the user's arm via the contact points it is needed to connect the exoskeleton properly with the human arm. As we mentioned before in order to give a force feedback to the shoulder ( $F_x, F_y, F_z$ ) we do not have to actuate all the DOF. In a typical configuration, as the one reported in Figure 7, where we are only interested in delivering a pure force, we only need to actuate three of the six DOF of the exoskeleton. Furthermore, in order to keep the inertia and the torque requirements of the actuation system low, we think of actuating only the first three DOF and let the last three (spherical joint) passive. This solution is also optimal for the mass distribution, since the barycenter is closer to the user's spine (the exoskeleton that sustains all the upper body weight).

To test the suitability and operation of the developed kinematic structure, a passive version of the system was constructed. This, depicted in Figure 8, reproduces the same mechanical functionality of the full system, but only has sensory capabilities (no actuators are mounted on the joints). We tested the device on different subjects and could validate our kinematic models and simulations results. The first prototype also suggests some improvements and the direction we need to follow to design the mechanics of the active system.

## VI. CONCLUSIONS AND FUTURE WORK

With this paper we presented a preliminary design concept for a multi-contact point haptic interface. We introduced a kinematic model for the human arm and combined it with real motion data in order to synthesize the kinematics of the exoskeleton. By realistic simulations we proved that the chosen kinematic configuration for the shoulder-joint fits with the human arm anatomy and does not restrict the shoulder movement. Future work will be focused on the study of the kinematics of the composite system of the human's lower shoulder and forearm together with a compliant exoskeleton structure. Furthermore, we will develop stable interfaces between the exoskeleton and the human body. Currently



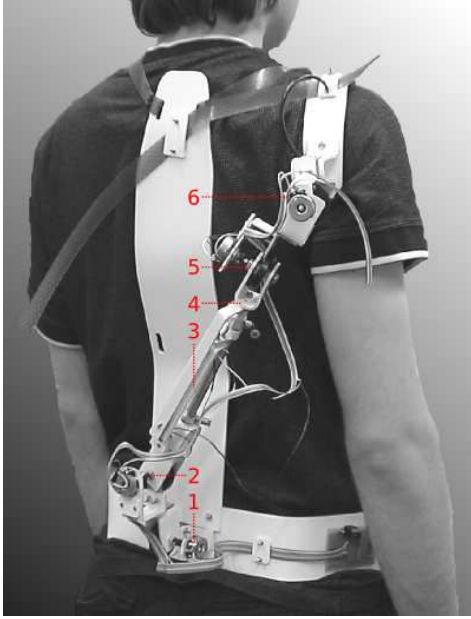


Fig. 8. The passive version of upper shoulder joint worn by a subject, enumerated DOF.

we are dealing with the experimentation of a light hybrid hydraulic-pneumatic actuator and of a control system that is able to regulate finely the force feedback and to change its impedance actively. Finally, we are developing control algorithms for the application of teleoperation with haptic feedback.

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