DESIGN OF A BIO-INSPIRED WEARABLE EXOSKELETON FOR APPLICATIONS IN ROBOTICS

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Abstract: In this paper we explain the methodology we adopted to design the kinematics structure of a multi-contact points haptic interface. We based our concept on the analysis of the human arm anatomy and kinematics with the intend to synthesize a system that will be able to interface with the human limb in a very natural way. We proposed a simplified kinematic model of the human arm using a notation coming from the robotics field. To find out the best kinematics architecture we employed real movement data, measured from a human subject, and integrated them with the kinematic model of the exoskeleton , this allow 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.

1 INTRODUCTION

In this paper a bio-inspired design approach to synthesize the kinematics structure of a haptic interface is introduced. The system presented is mainly intended for applications in the field of the tele-robotics systems; nevertheless can also be effectively employed as a sophisticated haptic interface during the interaction with a virtual environment or during a training or rehabilitation session.

In interaction with a human an exoskeleton can provide two main functionalities: First, it can be used as an *assistive device*, e.g in physiotherapy an exoskeleton can be adopted for movement enhancement (Gupta et al., 2008) (Carignan et al., 2005), in other scenarios it can be used for performance augmentation (Dollar and Herr, 2008).

Second, an exoskeleton can be used as an *input device*, enabling a human operator to manipulate either a virtual or a real target system. The latter use-case – which is called *teleoperation* surrenders in any situation where work has to be done in regions, in which it is unfavorable or even impossible to work as a human. Possible applications for teleoperation occur in *telesurgery* (Bar-Cohen et al., 2001), *aerospace* (Schiele and Visentin, 2003) and *underwater* (Kwon et al., 2000).

The primary aim of an intuitive teleoperation is to allow a human operator to see and feel the remote environment, as a secondary aim he further should be able to attribute himself with the target robot (IJsselsteijn et al., 2006). A general overview about the topic of teleoperation is given in (Hokayem and Spong, 2006).

In case of teleoperation an exoskeleton acts as an human-robot *haptic interface* which is “nothing but a bidirectional mechanical transducer”(Hayward and Astley, 1996). Ciriteria for the quality of haptic feedback are given in (Hayward and Astley, 1996), comparative studies are are presented in (Griffin et al., 2005) or (Yu, 2003).

The hardware of existing constructions of exoskeletons differ in their *degree of activity*: On the one hand pure passive devices were developed by (Song et al., 2005) and (Chen et al., 2007, ZJUESA). On the other hand empowering exoskeletons were built up, see (Dollar and Herr, 2008). Between these extrema one finds exoskeletons acting as force-reflecting controlling devices. These can be further categorized into solutions which are fixed to an external basis (Mistry et al., 2005) and (Perry et al., 2007) and those remaining wearable. The latter is described by the study in (Kim et al., 2001).

In the next following section we introduce the model used during the design process, we also presents some results from the study we conducted on a real human subject in order to analyse the importance of the Clavicle-Scapula articulation during the

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shoulder movement. Section 3 deals with the kinematic model of the exoskeleton, in particular here we reported only the system that is supposed to be coupled with the shoulder of the user. In section 4 we propose a possible design for the exoskeleton and present some preliminary results. Finally section 5 draws out the conclusions and the future developments.

2 HUMAN ARM STUDY AND KINEMATIC MODEL

The Human Arm represents one of the most advanced manipulation system we can find in nature. It is the product of an evolutionary process lasted 3.7 billion years (origin of life on the Earth). Its kinematics is defined by the configuration of different bones and articulations, these elements represent the structural components of the limb. Grossly we can divide the arm in two different parts: the upper arm and the forearm. The upper arm is represented by the segment that goes from the shoulder to the elbow, the forearm the segment that goes from the elbow to the hand.

Starting from the sternum (see picture 1), that for us represent the reference base, and moving toward to the distal part of the limb, we can encounter the following bones : Clavicle, Scapula, Humerus, Radius, Ulna, Carpus Bones, Metacarpus Bones, Phalanxes.

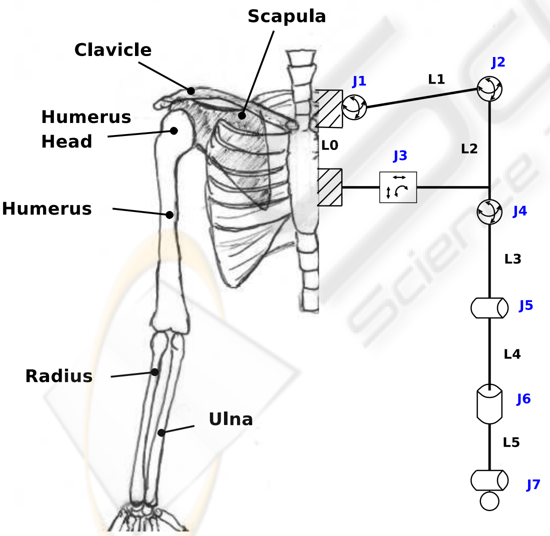


Figure 1: Representation of the skeleton of the human arm and its 10 DOF simplified kinematics model using a robotics notation.

In literature we can find different kinematic models for the human arm (Klopcar and Lenarcic, 2005), (Schiele and van der Helm, 2006), each one oriented to describe certain aspects rather than the others; As in (Schiele and van der Helm, 2006), to represent the kinematic model of the human arm, we used a notation related with the robotics field this 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 fits well.

The model formalized is represented in figure 1 (right side), again we can separate the kinematic architecture in two different parts: Shoulder Kinematics, Arm Kinematics. The shoulder Kinematics is composed by four joints, three spherical (3DOF) and one planar. More in detail the planar joint can be decomposed in two prismatic and one rotational joint, however in this first representation we preferred to use a compact notation. It also should be noted that the shoulder kinematics can be further separated 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, joint-1 (spherical) is located between link-0 (the link with the inertia reference system) and link-1, joint-2 (spherical) is located between link-1 and link-2, and finally joint-3 (planar) close the kinematics chain connecting link-2 and link-0.

The first consideration we can do on this kinematic chain is about the overall mobility. The three joints have a total of 9 DOFs, however because of its parallel nature there are some constrains that limit the mobility. We can define q as the configuration variable, this is a vector with m components ($q \in R^m$) that define unambiguously the position and the orientation of the all rigid bodies that compose the kinematic chain. We consider in this case only minimal configurations, this means that is not possible define unambiguously the system with less than m scalars.

Given the kinematic chain we can calculate the dimension for q applying the Kutzbach-Grübler formula (Zhao et al., 2004) :

$$m = 6(n-g-1) + \sum_{i=1}^{g} f_i \qquad (1)$$

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

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

This mean that this chain has overall three degrees of freedom, therefore to define unambiguously its kinematic configuration we can just define only three scalars. The model differs from (Schiele and van der Helm, 2006) for the presence of an additional DOF that allows to represents better the human anatomy. The question that arise now is: which joints variables we have to chose to define the configuration of the shoulder, in theory it is possible to chose just three variables from the nine we have. In practice we will see that there are some choices that are better than others, this especially if we need to measure these quantities in a real system.

Starting from the joint-4 the human arm can be represent as a open kinematic chain. As we can see from picture 1 joint-4 (lower part of the shoulder) connects link-2 to link-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 toward the distal part of this model we encounter joint-5 (the elbow) that connect link-3 with link4, this is a one DOF rotational joint that allow forearm flexion and extension. Finally we have joint-6 (first degrees of freedom for the wrist) that connect link-4 with link-5. In comparison with the human arm anatomy this represent a simplification, indeed in human beings it is a complex movement of both radio and ulna bones that allows 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 the case the results obtained will be not satisfactory.

In picture 1 we represented also the other joint for the wrist, joint-7, this has a total of two degrees of freedom that in the human arm allow the wrist flexion-extension and adduction-abduction. At the moment the hand kinematics is not considered in our study.

2.1 Analysis of the Arm Movements

In order to better understand the kinematic of the human Arm, and to start the validation of the proposed model, we conducted a first experiment where we acquired the trajectories of different points of interest located on the surface of the Arm. We applied a total of 19 markers (see picture 2) on a male subject (height 1.7m.) 3 along the spinal cords, 3 on the scapula, 1 on the top of the shoulder, 3 for the shoulder ring, 1 in the middle of the upper arm, 3 in the elbow ring , 1 in the middle of the forearm, and 4 in the wrist ring. We wanted to acquire the trajectories of all the parts of the Arm that are involved during the performance of an arbitrary movement. In the first experiment we asked the subject to perform a movement of flexion and extension of the shoulder. The rotation was relative to an hypothetical axes orthogonal to the sagittal plane, of course due to the complex kinematic of the shoulder this axes is not fixed, but changes according with the shoulder movements.

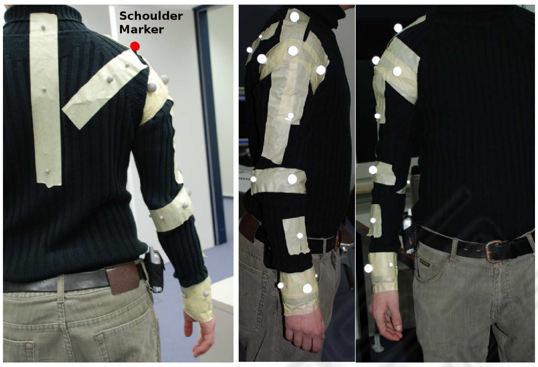


Figure 2: 19 Markers were fixed on the surface of the subject's arm.

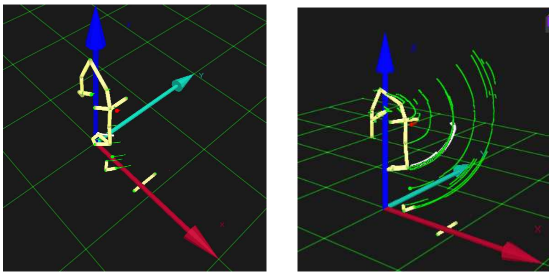
The Experiment where done using a commercial motion tracking system by *Qualysis*®, we employed the version with three cameras.

We chose an arrangement in order to avoid as much as possible the landmarks occlusion during the planned movement.

During the acquisition subject was located near the reference system, and was asked to perform the movement of the arm trying to keep fixed as much as possible the rest of the body.

After data acquisition and post-processing, it was possible to analyze the results visually, and to export the data in text format for a further elaboration by Matlab. The analysis of the movement by the *QualysisTrackManager*® showed many interesting features and behaviors. We noted that from the first phase of the extension movement all the bones of the upper shoulder are involved. We could recognize this by observing the trajectory of the markers located on the top of the shoulder, and in proximity of the scapula (figure 3a).

This means that it is very difficult to separate the movement of the lower shoulder from the movement of the upper shoulder, it turns out that we need to consider the entire shoulder kinematics from the beginning of the exoskeleton design. In picture 3 (b) we can see the trajectories followed by the markers for quite the complete extension movement (90%), it appears that many of them have a circular pattern, this is natural if we think at the kinematic structure of the human shoulder.



a. b.

Figure 3: (a)First part of the movement, it possible to note that the markers on the top of the shoulder start to move (b) Trajectories followed by the markers during the 90% of the extension movement.

3 THE EXOSKELETON KINEMATIC

The exoskeleton kinematics is strongly influenced both by the human arm anatomy and the performances we want to reach. The central idea is to try to restrict the mobility of the user's arm as less as possible when he is wearing the exoskeleton. Other desiderable requirements for the overall system are:

- Lightweight construction
- A system easily wearable
- Multi-contact points haptic feedback
- Modular design

All these goals are important to synthesize the kinematic structure for the exoskeleton, but for an initial analysis, the overall mobility constrains and the necessity to have multi-contact point haptic interface, represent our most relevant aims.

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

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

In order to provide the user a broad haptic feedback, our exoskeleton will transmit forces and torques via multiple contact points. One of these we have already defined 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. This locations are optimal in the sense that they reduce the interference with the human articulation during the user movements. One can see these three different contact-points represented in figure 4.

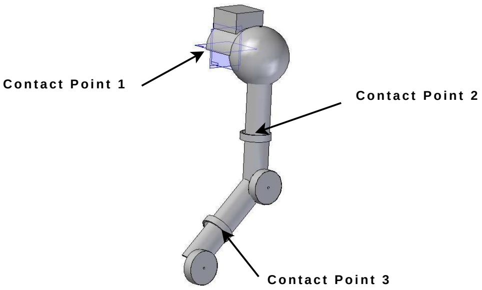


Figure 4: Contact points between the exoskeleton and the human arm.

3.1 Coupling the Exoskeleton with the Human Arm

It is important now to do some considerations about the overall kinematics that we obtain combining the arm with the exoskeleton. This will also help us to setup how many degrees of freedoms are required for the exoskeleton.

The next paragraph will concentrate only on the exoskeleton's kinematics that deals with the shoulder and the upper arm of the user, even if we have already started to extend the analysis also for the forearm. This omission is also justifies by the fact that at the moment we tested on a human subject only this part of the exoskeleton.

3.1.1 The Upper Shoulder Joint

Here we the term joint we want to refer to the entire kinematic structure for the mechanical system that is charged to deal with the upper shoulder (clavicle-scapula articulation). How many degrees of freedom should have this joint? From the motion analysis on the human arm it comes up that the upper shoulder has a total of 3DOF, but again in order to design the exoskeleton joint it is necessary to do some assumptions about its kinematics. A possible configuration is presented in figure 5 (upper part) here we can see that now we have a complex structure with different closed paths.

In order to study the system we can do a first simplification substituting the upper shoulder kinematic with a single joint with 3 DOF, in this case we have a simplified structure showed in figure 6.

Now it is possible to apply the theory in order to find the overall mobility of this configuration, we can calculate the number of DOF's with equation 3.

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

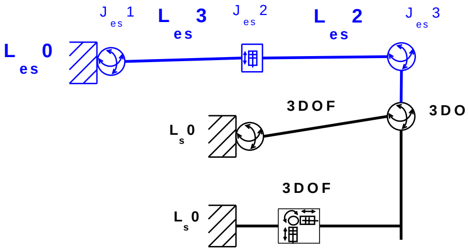


Figure 5: Closed kinematic chain formed between the exoskeleton shoulder joint and the upper shoulder kinematic chain.

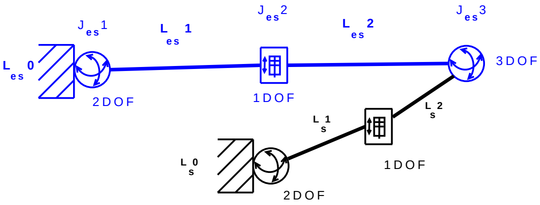


Figure 6: Equivalent model.

As is represented in figure 6 the exoskeleton has a total of 6 DOF; because we need to actuate a 3 DOF kinematic chain, it means that only 3 of the 6 DOF must be actuated and sensed. From a mechanical point of view it is more suitable to actuate the joints ($J_{es}1$ and $J_{es}2$) that is near to the barycenter of the body, in this way the actuation system is not required to move also the weigh of the actuators itself, this come clear if you think to the torque that can exercise a weight localized near the joint $J_{es}3$ to the joint $J_{es}1$.

3.1.2 Model Simulations

To fix some specifications for the actuation system of the exoskeleton we formilized a kinematic-dynamic model of the exoskeleton shoulder-joint using the toolbox SimMechanics in Matlab-Simulink environment. The system is composed of a spherical joint and a prismatic joint (see picture 7).

The initial point for the exoskeleton joint is coincident with the middle landmark along the spinal cord (see section 2.1).

In order to analyze the motion in a realistic way, we constraint the point P (see picture 7) to lie on a trajectory. We imposed as a trajectory the one we obtained from the motion analysis of the human arm performing an extension-flexion movement of the shoulder (underlined Marker in picture 2). To constrain the point on the desired trajectory we apply a force field directly on the point that was generated using a MIMO (Multi Input Multi output) PID controller, parameters of this controller were not optimized because we wanted only to perform a kinematical test of the system. The PID in question can be represented using a diagonal matrix:

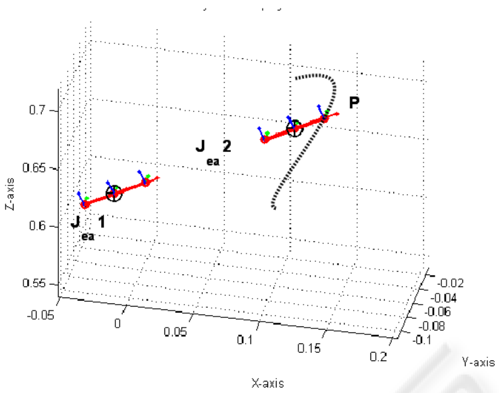


Figure 7: Simulation for the Shoulder Joint, measures in meters.

$$\begin{pmatrix} P{=}0.4,I{=}0.1,D{=}0.3 & 0 & 0 \\ 0 & P{=}0.4,I{=}0.1,D{=}0.3 & 0 \\ 0 & 0 & P{=}0.4,I{=}0.1,D{=}0.3 \end{pmatrix}$$

This means that only the position error along the X-axis will effect the X-component of the force, and the same for error along Y- and Z-axis. The results of this simulation is reported in picture 8, as it possible to see the force field generated is able to constrain the point trajectory (thicker line) near the reference trajectory (thin line).

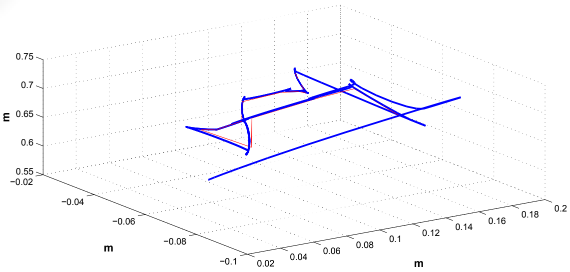


Figure 8: The trajectory followed (thicker line) by the point located on the upper shoulder, the thin line is the reference trajectory acquired from a human subject.

Once we are sure that point P is well constrained we can monitoring the position of each joint of the exoskeleton in order to evaluate the range of its movement, this is very useful to obtain same specifications for the design of the real system. In the graph of picture 9 we can see the linear position of the prismatic joint, how it is possible to note the range for this subject is about 0.08m (8cm). Of course it is necessary to perform this analysis on different subjects if we want to have a system that can adapt to different arm sizes, this will be the subject of future work.

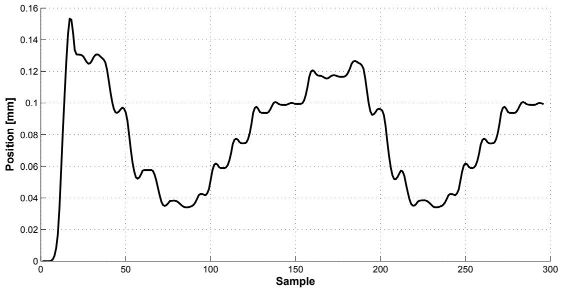


Figure 9: Range for the prismatic joint.

Figure 10 reports the angular positions of the spherical joint in convention of the Euler angles (roll, pitch and yaw). Therefore if we want to obtain the angular position of the exoskeleton we should do in sequence three rotations along X,Y and Z respectively.

Again we can evaluate the excursion for each single angle, from figure 10 we can see that roll range is about 30^o, the pitch 50^o and finally the yaw 15^o.

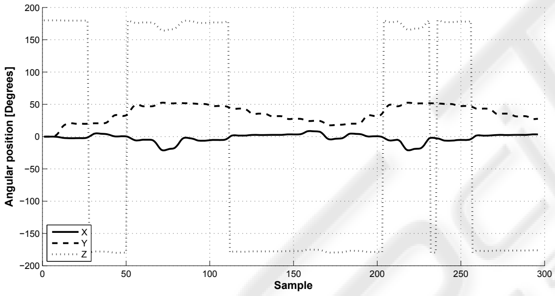


Figure 10: The three Euler Angles for the spherical joint.

3.1.3 Lower Shoulder Joint

Considering the lower shoulder (upper arm) combined with the upper part of the exoskeleton (figure 11) one can identify a closed kinematic chain. It starts at the link L_a0, crosses join J_a1 (the user shoulder), goes toward the contact point one (where the exoskeleton is fixed with the user upper arm) and then encounters in the order $J_{ea}3$, $J_{ea}2$ and $J_{ea}1$ that belong to the exoskeleton. Finally the kinematic chain ends with the link $L_{ea}0$ that in this case coincides with L_a0. We have also to observe that in picture 11 L_a1 and L_31 should be considered as a single link. Supposing now that $J_{ea}1$ is a 2DOF rotational joint, $J_{ea}2$ is a 1DOF prismatic joint and $J_{ea}3$ a spherical joint we can calculate the overall degrees of freedom of this closed kinematics.

$$m = 6(n-g-1) + \sum_{i=1}^{g} f_i = 6(4-4-1) + 9 = 3 \quad (4)$$

Equation 4 shows that combining the exoskeleton with the arm brings to a system that has three degrees of mobility (user upper arm), of course this do not guarantee that the mobility we obtain is similar to the mobility of the user upper arm. This is due to the fact that Kutzbach-Grübler formula do not takes in account the configuration of the joint, but only the total number of joints and degrees of freedom. For a more precise analysis, a possible solution is to perform a series of simulations, this will hallow us also to explore different configurations with different parameters.

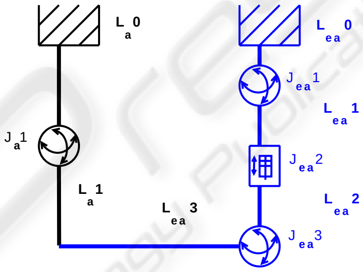


Figure 11: Kinematic representation of the exoskeleton coupled with the user upper arm.

4 EXOSKELETON DESIGN

From the data analysis of the extension/flexion movements of the shoulder it clearly appears that it is necessary to consider the overall shoulder complexity in order to define the exoskeleton kinematic.

However, in order to simply the design process, it is still possible to assume the point defined on the upper-lateral part of the shoulder as a starting point where to fix the kinematic structure that will follow the lower shoulder movements.

Therefore we separated the exoskeleton design in two different parts: one that deals with the upper and the other with the lower shoulder. In the following we explain a possible solution for the upper shoulder joint.

4.1 Upper-shoulder Joint

The mechanical structure is composed by four joints: a sequence of two rotational, one prismatic and one spherical joints. In figure 12 we can see a first concept for this structure, were we can note that there are two connection structures: one that is intended to be fixed to the user pelvis (the belt), and the other that is intended to be connected with the top side of the user shoulder. We want to employ rigid materials for these two parts in order to have a stable connection with the human body, but of course, we need also to shape these parts in order to be comfortable for the user.

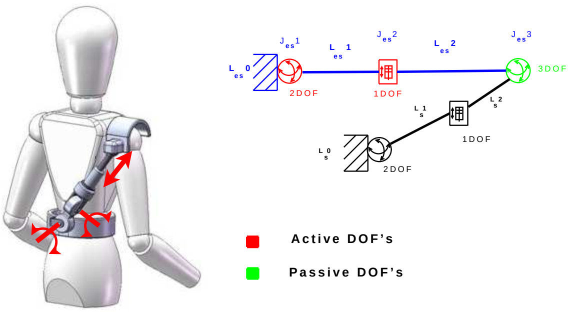


Figure 12: The Upper-Shoulder joint Exoskeleton concept and its kinematic structure.

exoskeleton. It is quite easy to fix the belt to the pelvis.

To design the device we should also take into account some important parameters:

- The exoskeleton length: this parameter should be adjustable in order to fit with different user sizes. Fortunately the length depends on the linear position of the prismatic joint, this means that the joint movement can be used to control the position of the user shoulder but also to adjust the device to the user size.
- The distance between the exoskeleton and the user back: this is important because if the exoskeleton is too near to the user back collisions will occur during the shoulder movements.
- The Shoulder-Connection dimension: this also depend on the size of the user shoulder, in this case it is necessary to build up a mechanism adaptable. A possible solution is to use an inflatable device, even if this will decrease the stability of the contact point.

Furthermore in order to keep low the inertia and the torque requirements of the actuation system, we can think to actuate the first three DOF and let passive the last three (Spherical Joint). This solution is also optimal for the mass distribution, in this case the barycenter is more near to the user spinal cords (the endoskeleton that sustains all the upper body weight).

To evaluate if the kinematic structure we assumed for the exoskeleton is suitable and efficacious, we decided to build a passive version of the system. This, depicted in figure 13, reproduces the same mechanical functionality of the system until the lower-schoulder-Joint, but has only sensory capabilities, indeed no actuators are mounted on the joints. We tested the devices on different subjects and we get a first impression on how the system works.

Figure 13: The passive version of Upper and Lower Shoulder-joint.

From this first qualitative analysis we obtain a very usefull feedback in order to guide the next steps for the design process. We noticed that the dimensions of the different exoskelton's links are not only important to fit the size of different users, but are also critical to keep the joints movements in a proper range. For example, if the link L_S2 (picture 12) is too long the prismatic joint is always completely retracted. This initial condition brings the system to lose some degrees of mobility. A solution for this problem is to dimension the exoskeleton in a manner that each joint, in its initial state, assumes a position in the middle of the possible range.

5 CONCLUSIONS AND FUTURE WORK

In this paper we described the design methodology we adopted to develop a multi contact point haptic interface. We introduce a kinematic model for the human arm and combine it we real motion data in order to synthesize the exoskeleton. We show by realistic simulations that the kinematic configuration we chose for the shoulder-joint fits with the human arm anatomy and do not restrict the shoulder movement. Future work will be finalized to better study the kinematics of the system that will deal with lower shoulder and the forearm and to test a complete arm-prototype. We need also to solve the problem of designing a stable interface between the exoskeleton and the arm and to develop a proper actuation system. At the movement we are dealing with the experimentation of a light hybrid hydraulic-pneumatic actuator that will be able to finally control the force feedback and to change the impedance actively.

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