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On the design of ergonomic wearable robotic devices for motion assistance and rehabilitation

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***Abstract*— The appropriate ergonomic design of a wearable robotic device is critical for the effectiveness of the device itself.**

In this paper we identified two key requirements for a structural ergonomics: the correct kinematic compatibility with the human limb and a comfortable and adaptable physical human-robot interface. We then show how the aforementioned requirements have been faced and implemented in the mechanical design of two wearable devices for elbow and hand rehabilitation, both developed at The BioRobotics Institute of Scuola Superiore Sant' Anna.

I. Introduction

To fulfill the requirements for an *ergonomic* design of a wearable robotic system for motion assistance and rehabilitation, the physical interaction between the human users and the elements of the system should be carefully taken into account. In particular, the ergonomic design of wearable robotic devices that are, by definition, parallel and physically coupled with a human limb should be compliant with the human model in terms of anatomical, anthropometric and biomechanical characteristics [1].

In the last decades a multitude of wearable interfaces for upper or lower limbs were proposed for rehabilitation or assistance of disabled people (e.g. [2],[3]). However, a critical analysis of the current state-of-the-art evidences that little attention has been paid in the appropriate ergonomic design of the majority of current wearable interfaces [4].

For a successful ergonomic design two main aspects need to be considered: the actuation/control and the mechanical/kinematic design of the structure.

In this paper we will only focus on the second point, since while most researchers are concentrating their work on improving the first aspect, the second issue is less investigated even if equally important. Indeed while sophisticated interaction control laws and variable impedance actuators can fulfill the requirements for providing the desired assistive and rehabilitation strategies [5],[6], the physical-human-robot interface (pHRI) of most of current wearable interfaces, does not always allow an effective *kinematic coupling* with the user limb and a comfortable force interaction.

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Both *kinematic compatibility* and *comfortable mechanical physical-interface* are essential requirements for ergonomics, and if one only of these two requirements fails, wearable robots lose their effectiveness and final end-user acceptability is affected. On one hand, if the kinematics setting of a wearable device is not correctly matched to the patient limb, undesired interaction forces can be generated during the motion of the device. Such joint-axes misalignment can then cause undesired translational forces on human articulations that, in the worst scenario, can lead to an uncomfortable or even painful use of the device [7]. On the other hand, instead, the specific choice of the mechanical interface influences the physical interaction with the user, so determining the perceived comfort and effort experienced by subjects [4]. These aspects become even more important if the final users are unhealthy subjects.

Rather, all types of wearable robots must be safe, comfortable and able to smoothly interact with each human user.

The goal of this paper is then to review and discuss the main design criteria for truly ergonomic mechanical design of wearable interfaces for assistance/rehabilitation. Furthermore, how these criteria have been fulfilled in the design of two wearable devices developed at the Scuola Superiore Sant'Anna is following shown.

II. Crucial Aspects in Ergonomics

An ergonomic system is able to provide a gentle and comfortable interaction with the human subject, by exploiting the full range of motion (ROM) of the human limb within its maximum natural workspace.

From a practical point of view this can be fulfilled *a)* if the system ensures the correct *kinematic compatibility* with the human limb and *b)* if the mechanical structure provides a *comfortable* and *adaptable* human-robot interface. Each single aspect will be analyzed in the following, by presenting two case studies of wearable devices for assistance and rehabilitation (i.e. NEUROexos [8],[9] and HANDEXOS [10],[11]), entirely designed at The BioRobotics Institute of the Scuola Superiore Sant' Anna and conceived to match the main requirements for a truly ergonomic design.

A. Kinematic compatibility

A key requirement for the pHRI of an ergonomic wearable robot is the correct and auto-adjustable alignment between the device and the patient's kinematic rotational axes. This is difficult to achieve for several reasons: firstly, the exact location of the human rotational axes cannot be easily identified because of its inner position in the limb. Secondly, biological joints are not hinge joints. Rather, they have complex joint surface geometries due to bones morphology which can cause little translation of joints centre of rotation and change of rotational-axis orientation along with the joint motion (i.e. human joints are loose hinge joints). Thirdly, fixation of a robotic device on a human limb is never rigid, but slippage between the device and the limb will occur because of tissue deformations. Additionally, inter-subject and intra-subject variability make difficult the adaptation to different users with variable anthropometry.

All these reasons are likely to create human-robot axes misalignment so that torques applied to the robotic joint would generate reaction forces on the correspondent human articulation. Such forces, if not compensated, can finally lead the exoskeleton to become ineffective or even be painful/dangerous for the user. Risk of injury and discomfort has been proved if the kinematic mismatch between the wearable orthosis and the user are not correctly compensated [12]. Furthermore, it has been shown that such kinematic mismatch can also alter the correct muscular activation patterns during physical therapy, so leading to possible injury [13].

A second common cause of kinematic misalignment between wearable robots and the human articulation arises from oversimplification of the human joint kinematics. For example, common mistakes are to model the human shoulder joint as a "ball and socket type" joint, or again the hand metacarpo-phalangeal (MCP) articulation as simple 'hinge' joint.

The most effective solution for providing the correct kinematic compliance with the human articulation is the introduction of passive DOFs or additional regulations along the kinematic chain. However this mechanical strategy are usually complex to be implemented and inevitably leads to bulky mechanical solutions (e.g. [14],[15]).

– *Case-study 1: NEUROExos*

Despite its apparent simplicity, the elbow joint behaves as a loose hinge joint because of its intrinsic laxity. Its peculiarity, indeed, is that the flexion-extension rotational axis traces the surface of a double quasi-conic frustum with an elliptical cross-section [16] notably dependent on inter- and intra-subjects variability (i.e. individual forearm characteristics and position).

NEUROExos is a powered elbow exoskeleton with a shelled link (Fig. 2). It has been then conceived in order to provide an active assistance of the flexion/extension elbow motion, but also to have an adjustable passive compliance with the laxity of the human elbow articulation. This choice allowed for a truly kinematic compatibility with the user's articulation within its natural ROM.

From a mechanical point of view, such kinematic compliance has been provided by mounting the active rotational joint of the NEUROExos with a 4-degree of freedom (DOF) passive mechanism, consisting of a closed-chain composed of 4 prismatic, 4 spherical, 2 circular sliders, 2 universal and 1 rotational joint [8]. These passive DOFs allow the flexion/extension rotational axis of the exoskeleton to rotate in the frontal plane of an angle of ±15°, in the horizontal plane of an angle of ±21° and to translate in the horizontal plane along the antero-posterior direction of ±15 mm.

Moreover, the NEUROExos forearm link can slide along the flexion/extension axis of a distance of ±15 mm. Lastly, the user's upper arm can slide against the NEUROExos upper shell through ad-hoc elastic bushings, so to unload the elbow articulation from any frontal-plane component of the misalignment translational force.

There is no evidence in literature of wearable devices that can provide such level of compliance towards the elbow kinematics.

– *Case-study 2: HANDEXOS*

Also the mechanical design of HANDEXOS, a powered hand exoskeleton, has been focused on the requirement of a kinematic coupling between the user's and the exoskeleton joints.

The full compliance with the complex anatomy of the

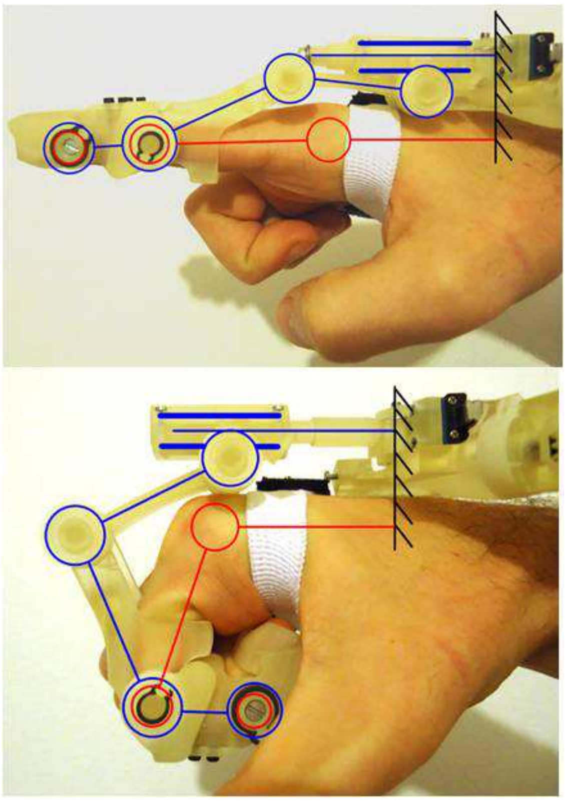

Fig. 1. Overview of the HANDEXOS finger module and kinematic layout in the extended (top) and flexed (bottom) configuration.

human hand is difficult to be achieved and nowadays represents one of the major challenges in robotics. Focusing on the HANDEXOS index finger module, it has been conceived in order to be compliant with the flexion/extension motion of each joint: MCP, proximal-interphalangeal (PIP) and distal-interphalangeal (DIP) joints.

However not all the hand articulations have the same anatomy: the PIP and DIP joints are hinge joints, with the head of the phalanx pulley-shaped with only one transverse axis; the MCP joint is an ellipsoidal joint that moves about two axes. In particular, during flexion the plate of the phalanx moves past the metacarpal head that has a variable radius of curvature [16]. This implies a variable relative distance between MCP and PIP joints.

So the MCP articulation is the most difficult to be assisted with a wearable hand device for the complexity of its anatomy that leads the center of rotation not to be fixed during finger flexion/extension. Moreover, differently from the other finger joints, its inner position in the palm does not allow to directly place a pulley on the joint's rotational axis.

From a mechanical point of view, the HANDEXOS PIP and DIP joints were implemented via revolute DOFs aligned along the PIP and DIP axes (Fig. 1), and equipped with an idle pulley for the actuation cable routing. In order to comply with their negligible misalignment, a soft cover in Neoprene was placed at the finger-exoskeleton interface in order to absorb potential axes misalignment.

For the correct kinematic compatibility with the entire user's finger, a self-aligning architecture [11] was developed for the MCP joint. It consists of a parallel chain made of two revolute and one linear DOFs (Fig. 1). This solution allowed to decouple joint rotation from joint translation, so allowing the transfer of the desired torque to the flexion/extension axis, without painful misalignment forces [7].

B. *Comfort and adaptability*

Other fundamental requirements for an ergonomic wearable device are the comfort of the structure and its adaptability to users anthropometry.

A truly comfortable device should have a lightweight mechanism and a wide distributed human-robot interface that does not cause discomfort or safety hazards during motion. Usually, in wearable devices the driving power is transmitted by means of connection band-cuff, while an increased contact surface can reduce the interaction pressure and thus the deriving stress/sore on the user limb.

Adaptability, instead, specifically refers to the possibility to fit different shape/size of the coupled human limb. If the anthropometric data (i.e. limb length and joints ROM) are not taken into account during the design of a wearable system, the device becomes unusable or even dangerous for the user.

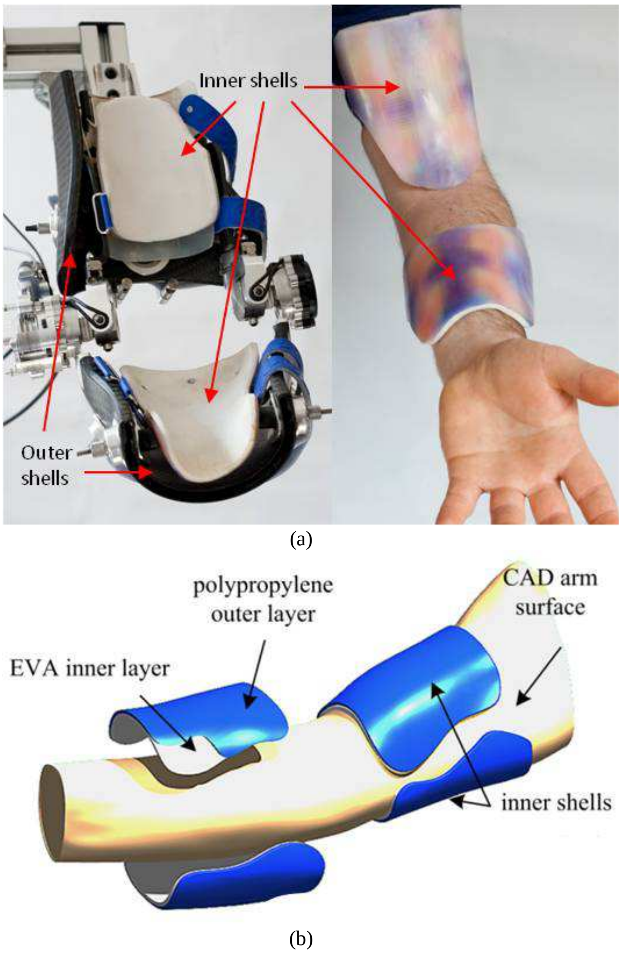

Fig. 2. Overview of the NEUROExos double-shell structure (a); detail of the inner shells, adaptable to the user's limb morphology (b).

Even if comfort and adaptability requirements are highly interrelated, an ergonomic design requires the individual accomplishment of each of them.

Indeed, as reported in [12] for the LOKOMAT leg orthosis, the fact that the system has been carefully thought in order to be adaptable to individual users, by keeping variable five different parameters (i.e. the alignment with the patients' hip, knee, and ankle joints), it does not guarantee a comfortable usage of the system. On the contrary, skin sores and stumbling of the patient were reported, due to the slippage of the orthosis cuffs during the training session.

– *Case-study 1: NEUROExos*

The NEUROExos links have been designed as a double-shelled structure composed of two concentric *shells*, namely inner and outer shells (Fig. 2a). The inner shells are then composed of two dorsal and two ventral shells, appositely designed on the morphology of the human limb (Fig. 2b)

Such a mechanical solution allows to overpass the common limitations of the typical bar-shaped links of most of the exoskeletons presented in literature (i.e. slippage of the connecting cuffs and non-distributed fixation pressure on the human limb, with consequent skin sore and discomfort). Rather, the shells shape ensures a gentle transfer of loads thanks to a wide interaction area and simplify the donning-on procedure. The latter being fundamental if users are non-collaborative patients.

The two carbon-fiber NEUROExos *outer* shells (one for the upper arm and one for the forearm) provide structural stiffness and strength to the exoskeleton, and transfer the load to the human limb segments. They also house the aluminium frames of the 4-DOF passive mechanism.

The two NEUROExos *inner* shells are passive orthoses made of an orthopaedic soft material (EVA foam + polypropylene), in contact with the dorsal and ventral sides of the limb segment (Fig. 2b). They can be thermo-shaped on a plaster cast of the user's limb of individual subject, in order to achieve a perfectly adaptable contact-area. Alternatively, a certain number of standard sizes of shells can be manufactured in order to fit most of the users anthropometry.

Inner and outer shells are connected by means of a customized mechanism of variable size that apart from its structural importance, also absorbs the undesired translational forces generated by the user-robot joint axes misalignment on the frontal plane by allowing variations in their relative spatial orientation.

– *Case-study 2: HANDEXOS*

Similarly to the previous case, also HANDEXOS has been designed with a shelled structure in order to allow a distributed contact-area with the finger's skin.

In particular, each phalangeal link has a C-shaped shell structure, appositely designed in order to both reduce the lateral encumbrance between two close finger modules, and to only burden the external lateral side of each finger. Such solution, also simplify the donning-on/donning-off procedure.

Furthermore, the compliance with the requirement of the adaptability has been fulfilled by endowing HANDEXOS with specific solutions for fitting the inter-subject anthropometric variability. In particular, the self-aligning MCP mechanism can absorb variations in dimensions of the first finger phalanx. The distal exoskeleton phalanx, instead, has been appositely designed with an untapped distal end, while the middle phalanx has an adjustable dovetail coupling, which can be adapted to the user's phalanx length.

III. Conclusion

A truly ergonomic wearable device smoothly interacts with the user's limb and provides a safe and comfort human-robot interface. In this paper we identified two main key-requirements for a structural ergonomics: the correct kinematic axes alignment with the human limb and a comfortable and adaptable pHRI.

Each single aspect has been then analyzed with two examples of practical implementation of the aforementioned requirements, starting from the analysis of the biological case to the definition of the appropriate mechanical solutions.

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