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MULT: a wearable Mechanical Upper Limbs Tracker designed for teleoperation

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***Abstract*—In this paper, we present a mechanical upper limbs tracking system designed for manipulation in teleoperation scenarios. In detail, it can track position and orientation of the hand palm. Since it is linked to the Mechanical Hand Tracker (MHT), developed in a previous work, the whole structure can track position and orientation of each fingertip respect to the torso. Such a mechanism can avoid typical limits of alternative tracking methods: occlusions for optical and artificial vision methods, and lack of precision for data gloves. Also, there is no dependence with a grounded, calibrated camera system, thus the wearer can move freely in the space. These features can better fit with certain scenarios such as teleoperation and industrial settings, where reliability of the tracking is of paramount importance. On the other hand, it is challenging to design a multi-dof mechanism that can adapt to different body dimensions, and allowing a large pose workspace. In this work, we propose a methodology to design a linkage mechanism preserving complete upper limbs and fingers mobility. Teleoperation tests assessed the functionality of the developed upper-limbs tracking in a pick-and-place scenario.**

***Index Terms*—teleoperation, upper-limbs tracker, hand tracker, mechanical tracker, Screw Theory, haptic feedback.**

Tracking the upper limbs pose is a well-known approach to target the own's motion in teleoperation systems. Tracking of the body pose is a largely investigated topic due to multiple applications, including motion capture, motion analysis, virtual reality, and teleoperation. The latter impose more strict requirements in terms of reliability that can motivate specific design solutions. In standard telemanipulation architectures, the objective is to estimate the wrist motion in real-time, with low-tremors level, and possibly not hindering the arm's workspace.

Extensive literature reported on techniques for motion-tracking-based teleoperation which can be grouped into three main approaches: i) vision-based systems; ii) mechanical tracking systems (manipulator or haptic interfaces); iii) wearable tracking sensors and suits. In this paper, we introduce a wearable Mechanical Upper Limbs-Tracker (MULT), shown in Fig. 1, designed for accurate tracking the hands dorsum for telemanipulation applications.

Vision-based tracking systems can be divided in systems using optical markers, and systems based on artificial vision. Optical markers, captured by a grounded and calibrated set of cameras, are nowadays a consolidated method in motion capture applications. They have been used also in telerobotics, starting from pioneer prototypes [1] to recently integrated commercial body suits and gloves [2]. More recently, methods based on artificial vision have been adopted [3], supported also by integration in commercial VR products, such as the Ultraleap device and the Oculus Quest 3D visor. The main limitation for optical tracking systems is the sensitivity to occlusions, as well as to adverse light conditions (i.e. direct sunlight).

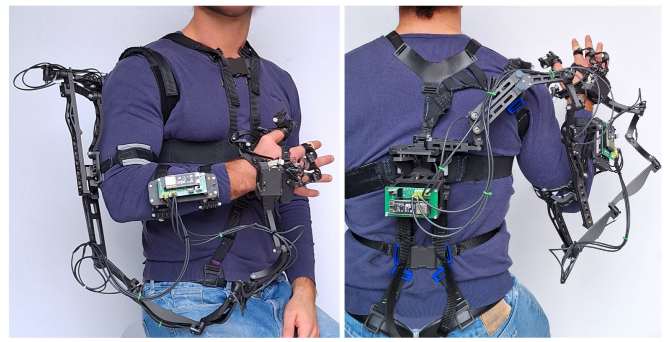

Fig. 1. The proposed wearable mechanical upper limbs-tracking system endorsing serial kinematic chains for precise hand dorsum pose estimation.

In wearable tracking systems, inertial measurement units (IMUs) are attached to human limbs to estimate the body pose, with the advantage of being independent from grounded sensors and highly wearable. Calibration of the skeletal model with the relative position of the sensing becomes then crucial for precise tracking. Pose estimation can be affected by drift, arising by integration of inertial sensors measurements, even after noise filtering and fusion methods [4], [5].

In telerobotics, such systems have been explored i.e. in [6] and [7], for telemanipulation task with a four-legged robot.

A different approach is represented by mechanical tracking system. When a robotic device is used as a haptic interface for the user, the position of the end-effector can be obtained from the joint sensors of the device.

This conventional approach is still implemented in current literature for teleoperation of avatar systems, in particular when the implemented interface is a grounded robot, used to render kinesthetic force feedback as well [8]–[10].

A similar approach can be transferred to fully wearable mechanical tracking systems; [11] and [12] proposed prototypes of wearable trackers in the form of exoskeleton links attached to the arm and the forearm.

With a similar paradigm, we have conceived the MULT system as a passive exo-suit, composed of a serial kinematic chain attached to the upper limb. Tracking is pursued only through joint rotations measurements that reconstruct the hand dorso pose with respect to the torso which is assumed as the global space frame. This is made possible through a direct kinematic model that computes in real-time the 6D pose of the end-effector (coincident with the hand dorsum) based on the readings of the joint encoders.

Compared to other wearable systems at the state of the art, the MULT allows: i) full upper limb mobility; ii) adequate degree of adaptability to different body sizes (especially arm and forearm); iii) compliance with encumbrance limits; iv) low-cost and lightweight due to 3D printing construction. Lastly, the device can integrate a mechanical hand-tracker system that we proposed in a previous work [13] to include in the teleoperation architecture fingers tracking and tactile feedback at the fingertips.

The paper is organized as follows: Sec. I discusses the kinematic upper limb model, and the design methodology to define the kinematics of the device. In particular, through an intuitive graphical methodology - based on the screw theory - we define the number, position, and orientation of the joints that satisfy the complete upper limbs mobility with the minimum number of joints. Sec. II is devoted to a preliminary experimental test with a first prototype setup. First, it was ascertained the full mobility in the entire upper limb workspace. Moreover, the suitability of the device for telemanipulation purposes was validated during a pick-and-place task. Sec. III synthesized the works and highlighted improvements for future applications.

I. Design of the Mechanical Tracking System

A. Kinematic Upper Limb Model

An upper limb model is necessary to design the MULT device (see ahead subsection I-E). In this work, the classical kinematic model proposed in [14] and [15] is adopted. As a first simplification, we neglect the small displacements that are due to the compliance of soft cartilage parts. Besides, the reciprocal rolling of bones on their mutual contact surfaces are modeled through ideal hinges. Consequently, a total of 9 DoFs is found from the clavicle to the back of the hand: 2 DoFs for the clavicle, 3 for the shoulder, 1 for the elbow, and 3 for the wrist.

Note that the backbone coincides with the global space frame. At this point, a preliminary choice is concerned with choosing the anchor points between the MULT chain and the upper limb. Several aspects have been considered, such as: i) ergonomics; ii) size; iii) general body joint mobility; iv) the possibility of multiple anchor points. Consequently, anchor points are distributed as follows:

- the first of the chain is located in a region of the back approximately between the shoulder, the scapula, and the neck. This anchor point is fixed and supports the weight of the whole structure;
- the second is placed on the homer. Because there is no unique chain that links the frame on the back to the hand directly, the location of this anchor point has been chosen based only on encumbrance constraints;
- the third and final is on the hand dorsum.

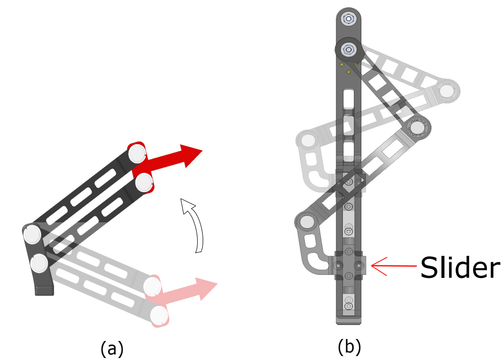

Fig. 2. Examples of mechanisms endorsed with sensorized pin joints and realizing a linear motion of the end-effector along a fixed direction. (a) A four-bar mechanism is arranged with links of equal length. In this condition, the rod translation occurs approximately along a fixed direction. (b) Crank-rod mechanism with slider end-effector.

B. Screw Theory Approach to the Kinematic Design

The kinematic design aims at finding the strictly necessary number of MULT joints/DoFs that ensure full upper limb mobility. Indeed, introducing increased lability DoFs might result in: i) increased complexity and weight; ii) further control effort during telemanipulation; iii) unresolved redundancy, i.e. non-uniqueness of a single configuration of the device for a given configuration of the measured joints position.

To this purpose, the Screw Theory (ST) methodology is adopted ([16]). The approach to this type of theory is discussed more in details in the work we proposed in the previous work ([13]).

Applying this theory, the end effector of a kinematic chain that has 6 indipendent DoFs can assume 3 distinct positions and 3 distinct orientations in space. In this way, if one end of the chain is fixed to the frame and the other is fixed to a body that can move and orient itself as it wants in space, the chain is arranged in such a way as to accommodate its posture. Consequently, MULT doesn't limit the wearer's motion if every chain between two anchor points has effectively 6 indipendent DoFs in the whole user's workspace (or RoM).

C. Principal kinematic joints adopted

In the case of small dimensions, pin joints are convenient with respect to other construction types, as it is well-known in the practice [17]. Hence all the DoFs of the MULT model were realized through combinations of pin joints. In particular, for translational DoFs two strategies were adopted whose details are discussed in Sec. I-E.

As shown in Fig. 2(a), a four-bar system can be an example of a pin joints mechanism realizing a linear motion along a fixed direction. Indeed, the rod direction (red arrow) is kept almost constant when the lengths of the links are the same. A further configuration is a crank-rod mechanism, shown in Fig. 2(b) that realizes a constant linear motion. Nevertheless, the four-bar is more convenient because this parallel kinematics has only 1 DoF, and thus only one encoder is sufficient to track the end-effector pose from measurements of pin joint rotation.

At the same time, it should be considered that the motion of the end-effector is only approximately constant in direction. This is because during the motion the centers of the pin joints describe two distinct circular trajectories. Even though, this ”combined” translation approximates a pure translation along a fixed direction the longer the links are and as long as the pin joints on the frame side become close to each other.

D. Working Principle of the Tracker

Results from Sec. I-B necessarily lead us to the following conclusion: between the frame (placed and integral to the back) and each anchor point (defined in the I-A), there is a single kinematic chain with 6 independent DoFs, that allows free movement of the wearer's upper limb. The only limit to this freedom from the presence of limit switches of each joint.

In this way, a given pose of the limb corresponds to a single pose of the MULT. Consequently, the pose of the last anchor point (end-effector or hand dorsum) can be solved by direct kinematics through the reading of the values of the joint variables provided by the encoders. Hence, despite the system composed by the MULT and the user being a parallel chain, the pose of the last anchor point can be found based only on the serial kinematic chain defined by the tracker itself.

E. Mechanical Tracker Design

According to the previous considerations, the MULT kinematic has a ”branched” structure that deploys from one point on the back with three branches closed on 3 distinct anchor points:

- the I° branch deploys from the back to a point - localized between the shoulder, the scapula, and the neck - in accordance with I-A. Fig. 3 shows how it is composed:
  1) 2 sensorized four-bar mechanisms realizing translation in the vertical and horizontal direction respectively;
  2) a non-sensorized slider realizes the third translation (so up to here, the chain has 3 independent translations);
  3) a not sensorized spherical joint that guarantees 3 independent orientations.

  This branch has 6 independent DoFs and allows the adjustment of the device position, thus improving its wearability. Since we are not interested in tracking the clavicle orientation and position, the slider and the spherical joint are passive, i.e. not sensorized. Instead, the four-bar mechanisms need sensorization because they also belong to the next branch of the kinematic chain.

- the II° branch deploys from the shoulder to the homer. Fig: 4 shows how it is composed:
  1) 2 sensorized four-bar mechanisms, (the same as the first branch);
  2) 3 pin joints with mutually perpendicular axes and with the first and third axes colliding on one point. In this way, we have realized a spherical joint with variable radius, i.e. the second pin joint allows the colliding point to move, thus obtaining 3 orientations;
  3) since only 1 translation lacks, the last joint is a slider. For the sensing of this joint, the configuration of Fig. 2(b) is applied.

  This branch has 6 independent DoFs. Through this kinematic chain, it is possible to estimate the position and orientation of the homer. Despite the homer pose is not of interest, its calculation is necessary to complete the chain and thus to estimate the hand position and orientation.

- the III° branch deploys from the homer up to the hand dorsum, as shown in Fig. 5.
  6 sensorized independent pin joints: the second, third, and fourth have parallel axes, thus realizing 2 translations and 1 rotation in the plane defined by the axes. The first pin joint allows the orientation of this plane. The fifth, sixth, and seventh pin joints have axes perpendicular to each other and colliding to a point, therefore simulating a spherical joint and realizing the last 3 rotations required by the reciprocity condition.

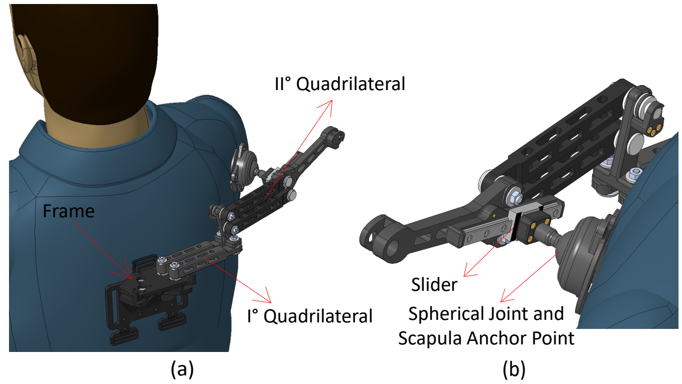

Fig. 3. First branch (back-shoulder) composed of 2 four-bar mechanisms, 1 passive slider, and 1 passive spherical joint.

Such a branched structure can be exploited to estimate the pose of the hand-dorsum with respect to the back in a cascade sequence: the hand-dorsum pose is calculated first with respect to the homer and then the homer pose is computed with respect to the back. 12 encoders are requested to solve the cascade.

It is worth noting that each branch allows a certain degree of adaptability to different user' sizes. The limit of adaptability is defined by the length of the links (each kinematic chain can cover a wide but limited range of sizes). This is a beneficial effect of using 6 DoF kinematic chains, in addition to the goal highlighted at the end of the Sec. I-B.

F. Hand Dorsum Pose estimation

To estimate the hand pose, two kinematics need to be solved in cascade:

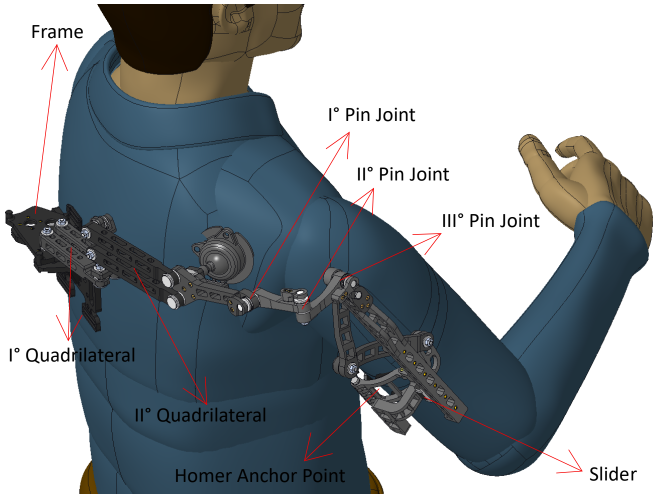

Fig. 4. Second branch (shoulder-arm) composed of 2 four-bar mechanisms, 3 pin joints and 1 slider mechanism (according to the schematic of Fig.2(b))

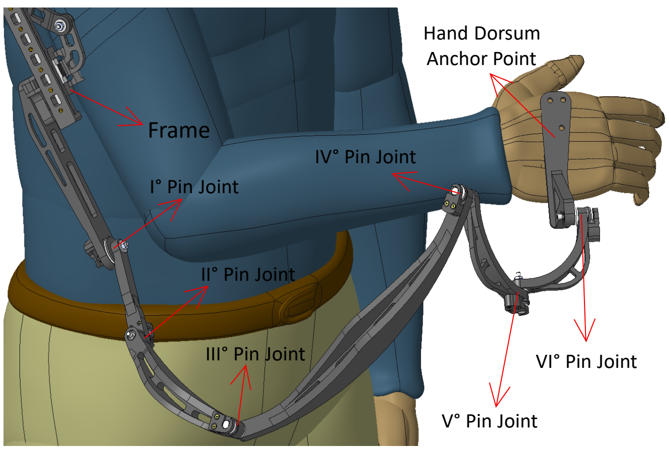

Fig. 5. Third branch (arm-hand dorsum) composed of a serial kinematic chain with 6 pin joints, combined to achieve a 6 DoFs kinematics.

1) the first defines the position of the interface for attaching the tracker to the homer with respect to the frame placed on the back;
2) the second defines the pose of the tracker attachment interface to the hand dorsum, as well as to the MHT hand tracker in [13].

To do this, it is necessary to appropriately establish reference systems integral with each link, and accordingly apply the compound rotation matrices and translation. In this regard, since the encoders read relative joint variables the composition in current axes is well suited. In this formulation, matrices are combined from left to right as one moves from the frame to the end-effector, as reported in the following. Starting from the reference frame S_0, to reach the reference frame S_2 passing through S_1, the composition is:

$$T^{0\to2} = T^{0\to1}\,T^{1\to2} \tag{1}$$

where: T stands for the general transformation matrix. Besides, homogeneous coordinates are useful in this case. Therefore, the general transformation matrix T_R related to a pure rotation (around an axis generally oriented in the space) and a pure translation (in a general direction) matrix T_T respectively, belonging to $\mathbb{R}^{4\times4}$, will take the corresponding form:

$$T_R = \begin{pmatrix} R_{11} & R_{12} & R_{13} & 0 \\ R_{21} & R_{22} & R_{23} & 0 \\ R_{31} & R_{32} & R_{33} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} T_T = \begin{pmatrix} 1 & 0 & 0 & d_1 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

G. Prototype construction and assembly

A first prototype of the MULT device has been built and assembled. It comprises:

- the frame, the anchor points, and the adjustments of the device are all made of a handcrafted combination of rigid nylon straps, elastic bands, and 3D printed quick-clip systems;
- each link of the MULT has been printed in nylon (Onyx filament printed with Markforged Mark Two printer);
- on the back frame, a PCB is placed together with its support. This PCB collects and supplies the 6 encoders of the branch from the back to the homer;
- on the forearm, a support is placed to host a PCB that acquires and supplies the 6 encoders of the branch from the homer to the hand dorsum.

The sensor adopted is a miniaturized absolute magnetic encoder RM08 by RLS with a resolution of 12 bits. PCBs are visible in Fig. 1 (colored in green). Each PCB accommodates an ESP32-S3-DevKitC-1 microcontroller from Espressif, which is supplied by Samsung. INR18650-35E Flat Top Li-Ion batteries (3.6 V - 3450 mAh). We chose cell batteries to easily replace them when discharged. The hand tracker uses a similar ESP32 board from Adafruit Industries. Each microcontroller acquires the encoder data and sends them to a host PC through a wi-fi connection at 100 Hz. The weight of the whole system is 1.554 kg which includes the branched kinematic chain, the tracker-wearer interfaces, and the sensing system (PCB, cables, batteries, and encoders).

II. Preliminary Experimental Assessment

A. Experimental Setup

As a preliminary functional assessment, we set up an experimental scenario, shown in Fig. 6, to evaluate the suitability of the MULT to target the own hand dorsum pose for telemanipulation tasks.

To this end, the operator is endorsed with the MULT on his right limb together with the Mechanical Hand Tracker (MHT) proposed in [13] (right hand). The MHT was also exploited as a fixed interface for the third branch of the MULT.

The remote system (follower) is a commercial manipulator, i.e. the 7 DoFs Franka Emika Panda mounted in a vertical layout, with the purpose of mimicking the human arm configuration. Besides, the end-effector of the Panda is equipped with the CORA Hand [18], here configured with 3 DoFs related to independent flexion-extension for the index, flexion-extension of the middle-ring-little finger assembly, and opposition for the thumb. Consequently, the MHT was equipped with 3 miniature

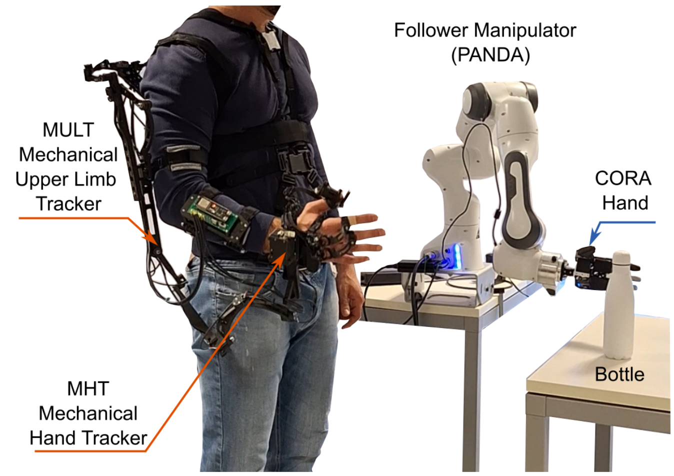

Fig. 6. Experimental setup arranged for a pick-and-place telemanipulation scenario. The operator is equipped with a first prototype of the MULT tracker (right upper limb) coupled with the MHT [13] hand tracker (right hand). The follower side is composed of a commercial manipulator and a custom robotic hand [18].

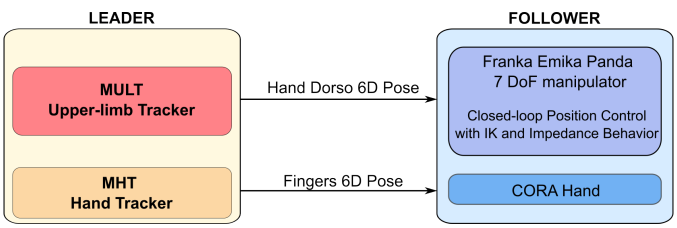

Fig. 7. Control architecture of the telemanipulation system. The leader system imposes the hand dorsum pose and the fingers flexion/extension angle.

potentiometers used to read the angles of the first phalanx joint of the thumb, of the index, and of the middle finger.

An illustration of the telemanipulation architecture is depicted in Fig. 7 in which the leader's and follower's system components and the exchanged signals are indicated.

The system components communicate through UDP/IP protocol using mixed wireless and wired connections: wireless link from MULT and MHT to the host PC; wireless between the host PC and the CORA hand; wired link between the host PC and the Franka Emika Panda manipulator. A host PC running a Matlab Simulink model in real-time merged information from the leader and follower sides.

B. Telemanipulation Test

As a first proof, we verified that the MULT prototype allows full mobility of the upper limb in the entire user's workspace, comprising singularity configurations, as shown in Fig. 8 (top). All these configurations were successfully reached by the manipulator end-effector.

Then, a second validation experiment consisted of the pick-and-place of a water bottle. The experimental procedures were approved by the Ethical Review Board of Scuola Superiore Sant'Anna (approval number 152021).

The experiment was performed indoors, with the operator and the follower in the same environment, at a distance of approximately 1 m. In this way, the operator could have direct visual feedback from the follower robot.

The bottle was placed on a desk, at a distance of 0.3 m from the hand of the manipulator and at the same height (0.9 m from the floor).

Namely, the operation requires picking the bottle from the table, moving it away from the table edge, and then placing it back on the table in the same original position (marked by a tape), as shown in Fig. 8 (down). The task was repeated ten times per person.

C. Discussion on a Qualitative Evaluation

Throughout the pick-and-place test, participant incurred in low number of errors, which are:

- collisions between the bottle and the table emerged especially in the first trials, due to the untrained operator's coordination between the arm's movement and visual feedback;
- imperfections in the implemented prototype could have deteriorated the precision of the tracking. The mechanical construction is made up of slender links which impact the orientation and relative position of certain joints, where the stiffness is lower. Consequently, the actual DoFs might have deviated from theoretical kinematics. Besides, it should be considered that in this first prototype, the building material was rapid-prototyping plastic. Hence, achieving the optimal design stiffness was more difficult;
- joint construction: pin joints were implemented through dry-friction bearing connections, and mechanical play was necessary to allow relative motion between the connected parts. This backlash also causes slight misalignment that can affect the overall estimation of the hand pose.

III. Conclusions and Future Work

We presented here a method based on screw theory to develop a mechanical upper limb tracking device, featuring adaptive kinematics with a passive linkage system. The approach builds upon previous work related to a hand-tracking device. Here, the combined system allows full upper limb tracking, from the user's torso to the hand and finger pose.

The mechanical tracking approach targets teleoperation applications, where the robustness of the tracking with respect to occlusions and adverse environmental conditions is very relevant. Alternative tracking approaches, widely used in VR and motion capture, are based on optical markers or vision, and cannot guarantee the reliability of the tracking in any captured pose or lighting conditions.

The design of the device, including the kinematic layout, sensor placement, and final parts design, faces the problem of adapting to the user body, covering the large workspace of the upper limb. The screw theory method is adopted to design the device with an adaptive kinematic approach.

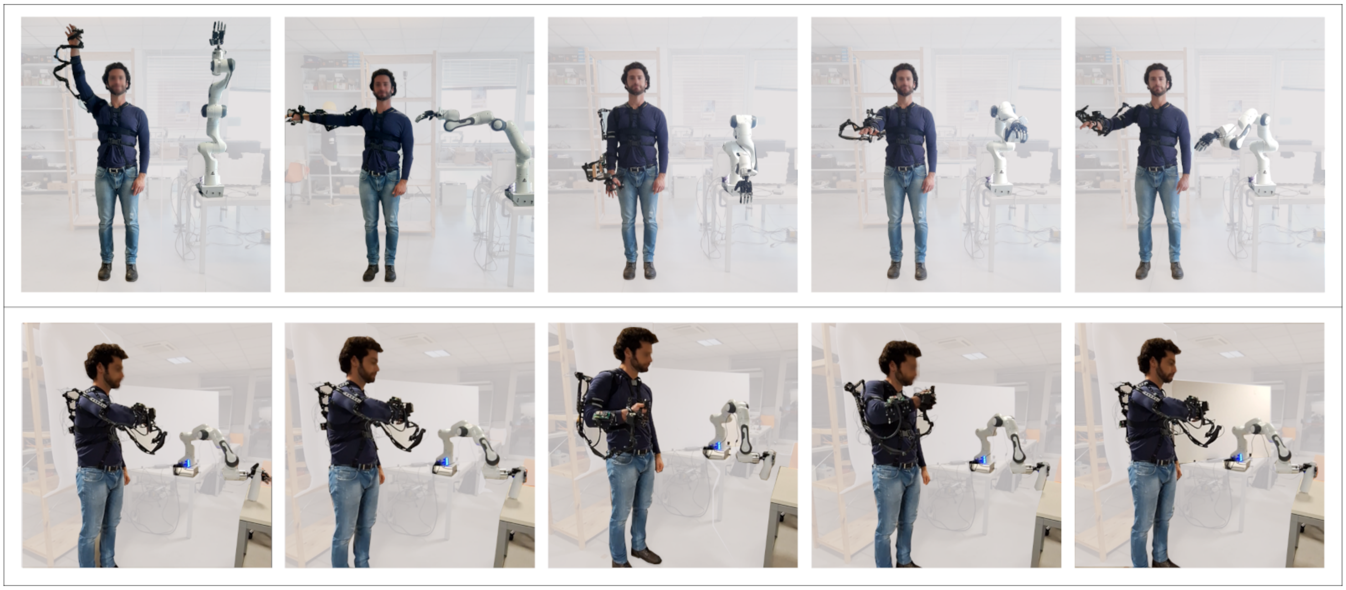

Fig. 8. Photo sequence of the preliminary experimental assessment. Top: the MULT allows full mobility of the upper limb in the entire user's workspace, comprising singularity configurations. Down: pick-and-place task sequence. The MULT targets the position of the user's hand to a commercial manipulator. Grasping is performed through a mechanical hand tracker combined with a custom robotic hand.

The final prototype was implemented with wireless electronics and then assessed in a preliminary teleoperation setup. It involved a static assessment in different poses, covering the upper limb workspace and singularities, and then in a pick-and-place task, here teleoperating a dexterous robotic arm and hand. These preliminary experimental results show the working functionality of the developed prototype and method. Further experiments will address more advanced manipulation scenarios, exploiting the large workspace coverage of the device and its intrinsic robustness to occlusions.

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