

Article

Proof of Concept of an Occupational Machine for Biomechanical Load Reduction: Interpreting the User's Intent

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Abstract

This paper presents a bench-top occupational power-assist robot aimed at reducing biomechanical effort during repetitive material handling. The prototype adopts a SCARA-like structure with three degrees of freedom and provides assistance on the vertical (z) axis through a three-phase brushless DC (BLDC) motor driven in field-oriented control with inner-loop current regulation. The user interacts with the robot through a single handle-mounted load cell. The measured interaction force is converted, via a calibration-based mapping, into a motor current reference that enforces a prescribed force-sharing ratio. In this way, the drive's embedded current loop acts as the low-level torque regulator, and the system can share gravitational and inertial loads without additional environment force sensing or explicit high-level impedance/admittance dynamics. A coupled electro-mechanical model is derived and used to select the assistance gain and to verify feasibility in simulation. A pilot experimental campaign with eight participants and two payloads (0.5 kg and 1.5 kg) was carried out on sinusoidal and random tracking tasks. With assistance enabled, the operator contribution was reduced to about 15% of the total load, and the mean bicep brachii EMG amplitude decreased by about 60%, while tracking accuracy was generally preserved and often improved.

Keywords: biomechanical load reduction; force amplification; power-assist robot; admittance control; human-in-the-loop; assistive material handling; BLDC current control; force sensor HMI

1. Introduction

In many everyday and professional contexts, people are required to manipulate and transport loads. In industrial assembly, for instance, human strength alone is often insufficient to handle parts or subassemblies safely and efficiently during production operations. Similar needs arise in agriculture and food processing, in civil construction, and in logistics environments such as warehouses, where repetitive handling of heavy objects is routine. Load handling is also critical in biomedical and caregiving settings, where patients may need assistance with sitting up in bed or being transferred to a wheelchair.

In addition to sheer force, these tasks frequently demand accuracy. Even when a fully prescribed spatial trajectory is not required, the object must often be positioned at a specific location and with a defined orientation. Maintaining precision becomes increasingly challenging as the handled mass grows, since human motor performance typically deteriorates under higher physical effort and fatigue.



Academic Editors: Andrius Dzedzickis and Xinjun Liu

Received: 28 January 2026

Revised: 21 February 2026

Accepted: 27 February 2026

Published: 28 February 2026

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For these reasons, robotic systems designed to amplify human strength have been investigated for many years. Such devices have been proposed as rehabilitation technologies [1–6], as assistive solutions [7–12], and more specifically, as strength-amplification systems for able-bodied users [13–15].

A broad related body of work has addressed upper-limb rehabilitation robots, EMG-driven orthoses, and haptic/force-feedback interfaces, highlighting different strategies for interpreting the user's intent and delivering assistance during functional movements [16–34]. In occupational settings, passive upper-extremity exoskeletons have also been investigated to reduce muscular effort during repetitive tasks [35–38].

In this paper, force amplification means that the machine allows the operator to perceive a constant (and tunable) fraction of the external load, i.e., the user supports only a controlled portion of gravitational and inertial forces while guiding the motion.

This work targets an occupational assistive device for vertical load manipulation in repetitive desk-scale tasks. The realized prototype is a SCARA-like arm mounted on a bench frame, where only the vertical prismatic axis is actuated; the remaining joints provide passive kinematic accommodation for the user during pick-and-place motions.

Relation to prior work. The present study builds on the same human-in-the-loop force-sharing concept previously explored by the authors, but transfers it to a motor-driven SCARA architecture and validates it through a dedicated calibration procedure and an EMG-based assessment on a redesigned prototype.

Conventional force-amplifying manipulators typically rely on intention sensing plus environment/contact force sensing to close an explicit force-feedback loop [39]. In this work, the sensing and control architecture is intentionally minimal: the operator's intent is inferred from the handle interaction force, and assistance is commanded by exploiting the motor drive's inner current loop (torque proportional to current). This enables regulation of the assistance level without external environment force sensors or an additional low-level force controller, while preserving the transparency and safety objectives targeted in physical human–robot interaction control [40–44]. These objectives are historically connected to hybrid position/force control and compliance/impedance formulations [45–47], including EMG-driven power-assist with impedance adaptation [48] and related electromechanical damping/compliance shaping approaches [49].

In practice, the operator steers the motion and “requests” assistance by applying a small force at the handle. The controller injects an amplified vertical actuation force so that the operator consistently feels only a tunable fraction of the overall load. For example, with a force-sharing ratio set to 6, a 60 N equivalent vertical load is perceived as approximately 10 N at the handle.

Contributions. This work contributes: (i) a minimal sensing/control architecture for vertical occupational load handling that achieves force sharing using a single interaction-force sensor and the motor drive's inner-loop current regulation; (ii) an explicit calibration-based mapping from interaction force to commanded motor current enabling a prescribed force-sharing ratio; (iii) an electro-mechanical model linking the human stiffness at the handle, actuation chain, and the resulting increase in apparent admittance of the coupled human–robot system; and (iv) a pilot experimental validation on eight participants quantifying force sharing, tracking accuracy, and EMG reduction during representative tracking tasks.

Compared with classical impedance/admittance controllers [40–43], the proposed approach intentionally leverages the user as the trajectory generator (via vision and proprioception) and uses only the interaction force at the handle to command assistance, avoiding additional environment force sensing and high-level dynamic control loops for the specific case of vertical load manipulation.

2. Materials and Methods

2.1. Mechanical Design of the Device

In the following sections, the entire development of the robot is presented.

2.1.1. Technical Requirements, Conceptual Design

The system to develop must be a proof-of-concept prototype that demonstrates the validity of the proposed solution for a system able to reduce the biomechanical effort during repetitive pick and place operations, with the ability to interpret the user's intention and to assist them during operations. So, no great attention will be put on materials to be used, allowing the possibility of realizing parts by 3D printing when possible.

As for the technical specifications, the device has to work on a desk on which parts have to be grasped and moved in repetitive little different translatory movements.

The technical requirements can be listed as follows:

- Mass to be moved: up to 5 kg,
- Working volume: 600 mm × 600 mm × 600 mm,
- Reduction of the user's biomechanical effort by the same percentage. The gain has to be settable,
- Ability to detect and interpret the user's intention and to give assistance in the task to be performed.

On the basis of the technical requirements, the concept illustrated in the schematic in Figure 1 was proposed.

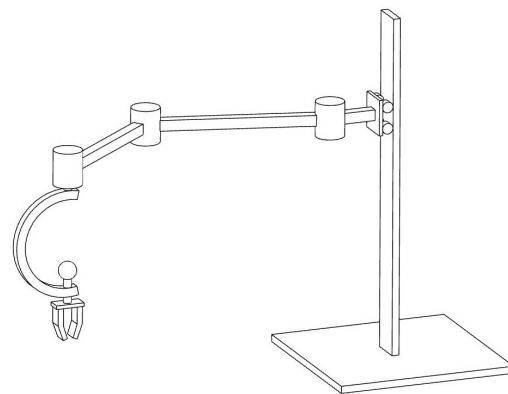


Figure 1. Concept of the device. The kinematic architecture is a PRRR SCARA type with the vertical translational joint motorized and the two rotational joints for the horizontal movements passive and actuated by the user.

The kinematic architecture is a PRRR SCARA type, and the idea is to motorize the z-axis to give aid against gravity. At the same time, the horizontal movements are left passive and are to be actuated by the user. The system can operate on a desk on which the objects that are to be subjected to pick and place operations are placed.

2.1.2. Direct Kinematic Model—Domain Analysis

To characterize the reachable workspace, the robot's direct kinematics were formulated using the modified Denavit–Hartenberg convention. Referring to Figure 2, the geometric parameters are reported in Table 1. The resulting working volume is shown in Figure 3. Detailed derivations and intermediate expressions are provided in Appendix A.1.

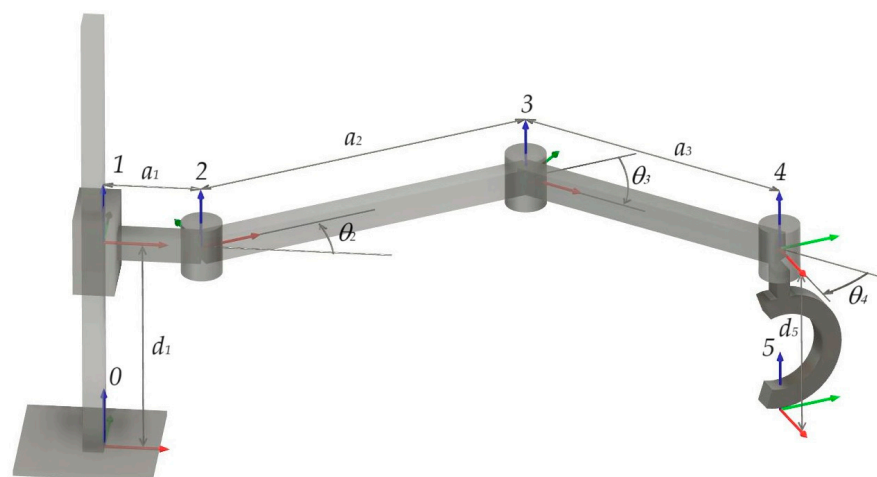


Figure 2. The kinematic architecture of the robot, geometrical dimensions, local references, and parameters for the kinematic analyses. Axes are color-coded as x (red), y (green), z (blue).

Table 1. Link parameters for the robot.

i	α_{i-1} [°]	a_{i-1} [mm]	θ_i [°]	d_i [mm]
1	0	0	0	d_1
2	0	136.5	θ_2	0
3	0	390	θ_3	0
4	0	330	θ_4	0
5(E)	0	0	0	−220

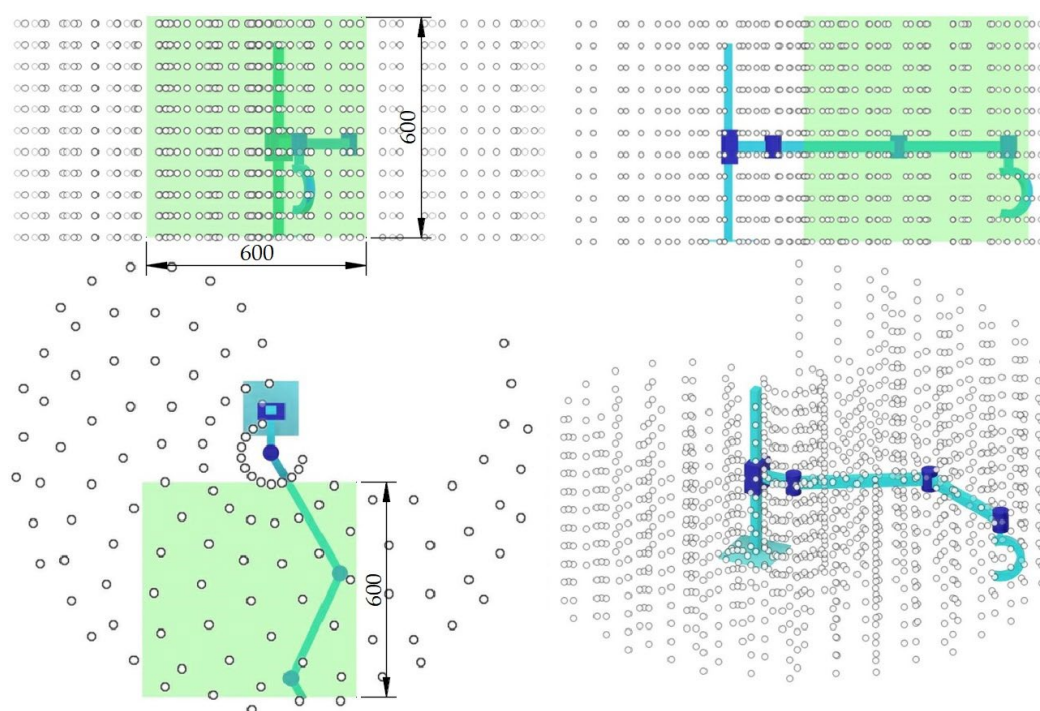


Figure 3. The working volume of the robot.

2.1.3. Inverse Kinematic Model

The inverse kinematics were derived to map a desired end-effector position in the horizontal plane to the corresponding joint angles, while the vertical motion is directly obtained from the prismatic joint coordinate. A compact schematic of the solution is reported in Figure 4; full derivations are reported in Appendix A.2.

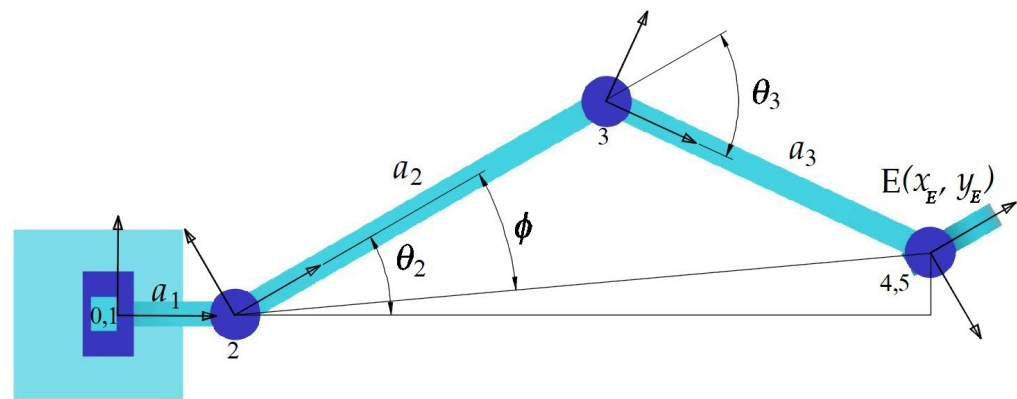


Figure 4. Scheme for the inverse kinematic solution.

2.1.4. Jacobian, Singularity Analysis

Although only the vertical axis is actuated in the prototype, the singularity conditions of the planar structure were analyzed to avoid configurations where small Cartesian motions would require large joint velocities. The Jacobian determinant becomes zero when $\theta_3 = 0$ or $\theta_3 = \pi$; the corresponding map over the workspace is shown in Figure 5. Full derivations are provided in Appendix A.3.

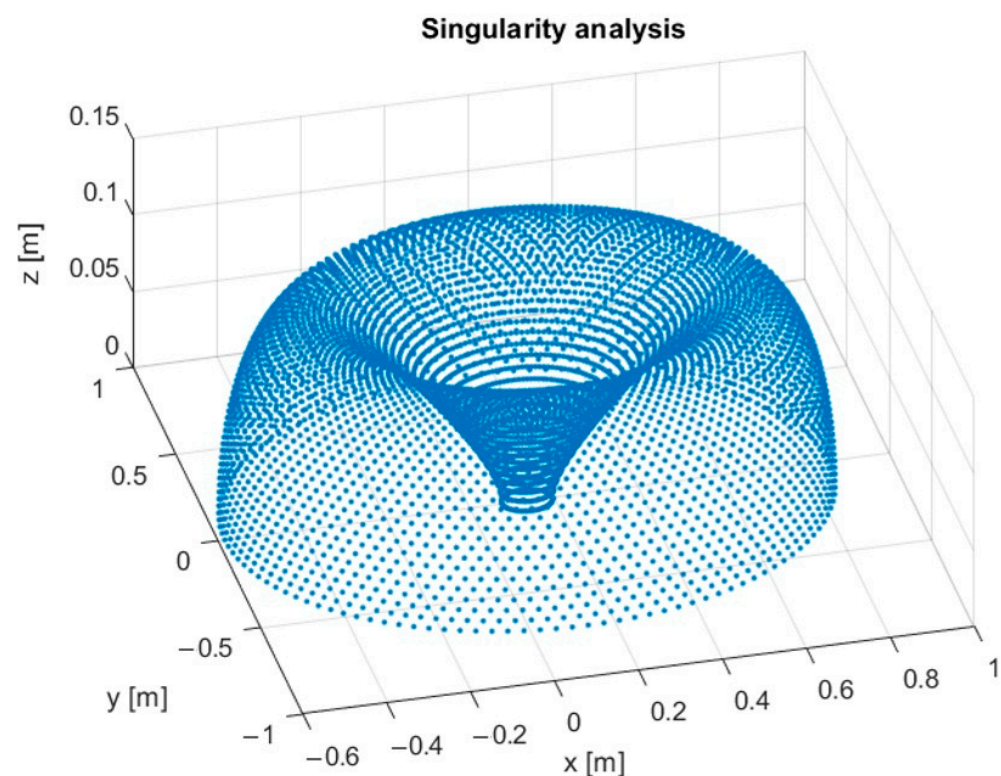


Figure 5. The singularity analysis over the robot domain.

The graph reports the spatial distribution of the Jacobian determinant over the robot workspace, highlighting the regions where the kinematic mapping becomes ill-conditioned. The points where $\det(J) \approx 0$ form boundary manifolds (inner/outer loci) corresponding to the fully stretched/folded configurations ($\theta_3 = 0$ or π). Operating away from these surfaces, the determinant remains bounded, implying well-conditioned velocity transmission and avoiding the large joint-speed amplification that occurs near singularities.

2.1.5. Dynamic Requirements—Actuator and Transmission Dimensioning

The dynamic need arises from the requirement of actuating the only vertical joint, i.e., moving the vertical translating masses. These are the carriage, the arm, the handle, the gripper, the sensor, and the load. Considering all the translating masses, but the load can be no more than 4 kg, the overall mass can be 9 kg.

Based on the considerations above, for the actuator, the choice was a three-phase Brushless DC electric motor (BLDC) with an exterior-rotor. The one chosen provides a nominal torque of 3.86 Nm, can be supplied by a voltage up to 48 V, has $p = 7$ pole pairs, is able to deliver a maximum current of 70 A, and has a back electromotive force of $k_{EBL} = 0.055$ Vs/rad, a torque constant of $k_{TBL} = 0.055$ Nm/A, a phase resistance of $R_{BL} = 39$ m Ω , a phase inductance of $L_{BL} = 2.81 \times 10^{-5}$ H, a mass of $m = 0.9$ kg and a rotor inertia of $J_r = 2 \times 10^{-4}$ kgm². It presents two shafts; the second one is useful for mechanical coupling with a position sensor. The position sensor is a capacitive encoder characterized by 4096 pulses/rev. In Figure 6, the BLDC electric motor (a) and the encoder (b) are presented.

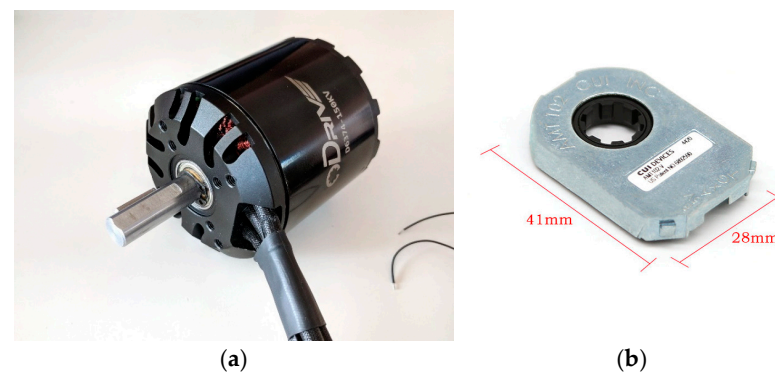


Figure 6. The BLDC electric motor (a) and the 4096 pulses/rev encoder (b).

Considering the actuator will be coupled to a pulley with a primitive diameter not bigger than 30 mm, it can provide the belt a transmission force of $3.86 \times 2/0.03 = 257$ N that can be considered sufficient to lift, gross of all passive resistance, the requested load of 89 N.

As for the transmission, a belt with T5 size, M type, with steel reinforcement wires was considered. The width was chosen to be 10 mm, which is characterized by an admissible load of 320 N.

2.1.6. Force Sensor

The load cell is mounted close to the end-effector, in the region naturally grasped by the operator. This is a load cell with a full scale of 10 N. It is equipped with a board with an amplifier and a 24-bit analog-to-digital converter. The board provides the power supply to the load cell by a 5 V signal. Then it detects the measure ready to be transmitted by a serial protocol to a microcontroller. The system, comprising the load cell and the board for amplifying and transmitting the data, was calibrated. By using two calibrated masses of 0.5 kg each, a constant was determined to obtain the data in N. In Figure 7a, a schematic of the chosen load cell with dimensions is presented, and in Figure 7b, the calibration relationship between mass applied and the returned value in N obtained by an ATmega328P microcontroller-based board, together with the acquisition board described above and visualized on a serial monitor application, is presented.

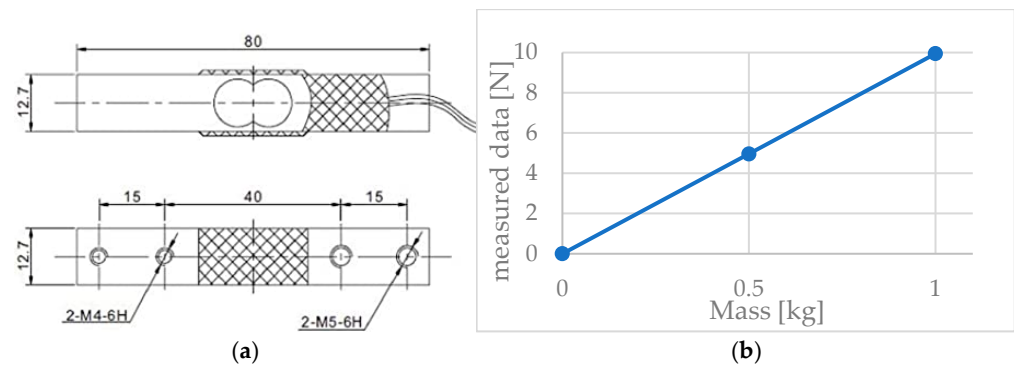


Figure 7. The selected load cell features an aluminum bar-shaped body: (a) dimensions and (b) calibration relationship.

2.1.7. Detailed Design

An aluminum plate 1000 mm × 800 mm × 10 mm is the main frame of the robot, on which a pillar is constrained. The column is realized using an aluminum square tube with a cross-section of 80 mm × 80 mm × 2 mm and constrained to the base by four aluminum squares with screws.

Inside the pillar fits the electric motor. The main shaft of the motor sticks out 25 mm and is coupled with the motor pulley. The rear shaft sticks out about 15 mm and is coupled with the encoder.

The vertical translational joint is realized by a linear guide, connected to the column, coupled to a carriage. The chosen components are a linear guide HGR25 with a section of 25 mm × 25 mm coupled with a recirculating linear ball bearing carriage HGW25HC. In Figure 8, a schematic of the carriage with the relative admissible loads is presented.

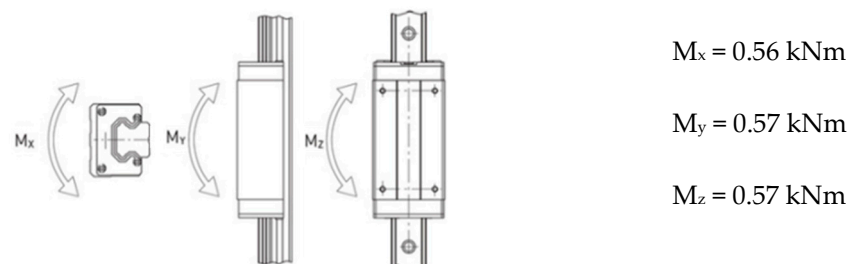


Figure 8. The chosen carriage guides are over-dimensioned and able to support all the admissible loads arising from the application.

The belt, a toothed synchronous type, is closed in a loop and runs from the base of the column, where it is engaged with the motor pulley, to the tip. At the tip, there is a plug that closes the column, making it the site of an axle, with two ball bearings, to which a pulley is connected as the belt return. One branch of the belt is connected to the carriage to give it motion. To do that, the carriage is screwed to a C-shaped aluminum component, which, on its side, is connected to a bracket connected to the lifting branch of the transmission belt to take the motion from it. Inside the C-shaped component is placed the shoulder of the arm, Figure 9.

The rotational joints connecting the two links and the shoulder make use of two thin ball bearings for robotics applications. The shoulder presents the grooves to couple with the outer rings of the bearings. Inside the inner rings of the bearings, the pin of the joint is coupled. The two parts are maintained together by a disc screwed to the end face of the pin, locking the ball bearing in the hole of the hinge. The pin presents a tang for coupling to the link of the arm. The joint of the elbow is similar to that of the shoulder (Figure 9).

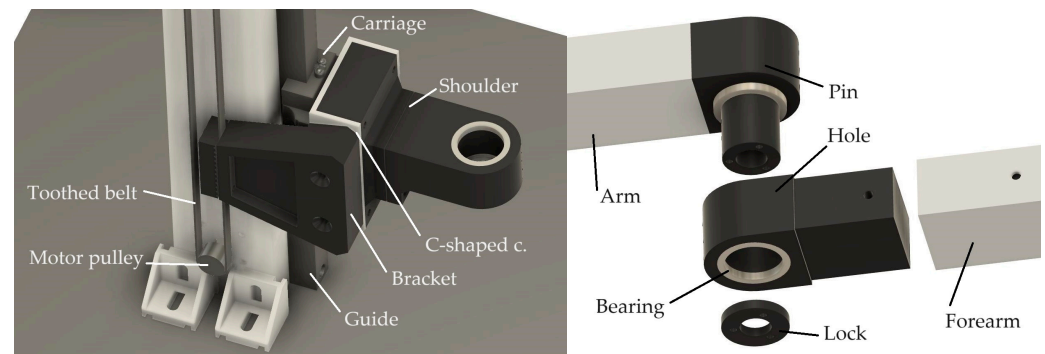


Figure 9. 3D CAD details of the proposed device.

The forearm ends with a tang to which a handle is connected through a rotational joint. On the lower external side of the handle, there is the end effector, which could be a mechanical, pneumatic, or other kind of gripper. On the lower internal side of the handle, there is a knob, which is the human-machine interface. In Figure 10, there is a 3D model of the entire device in which it is possible to see the handle, the gripper, and the HMI knob.

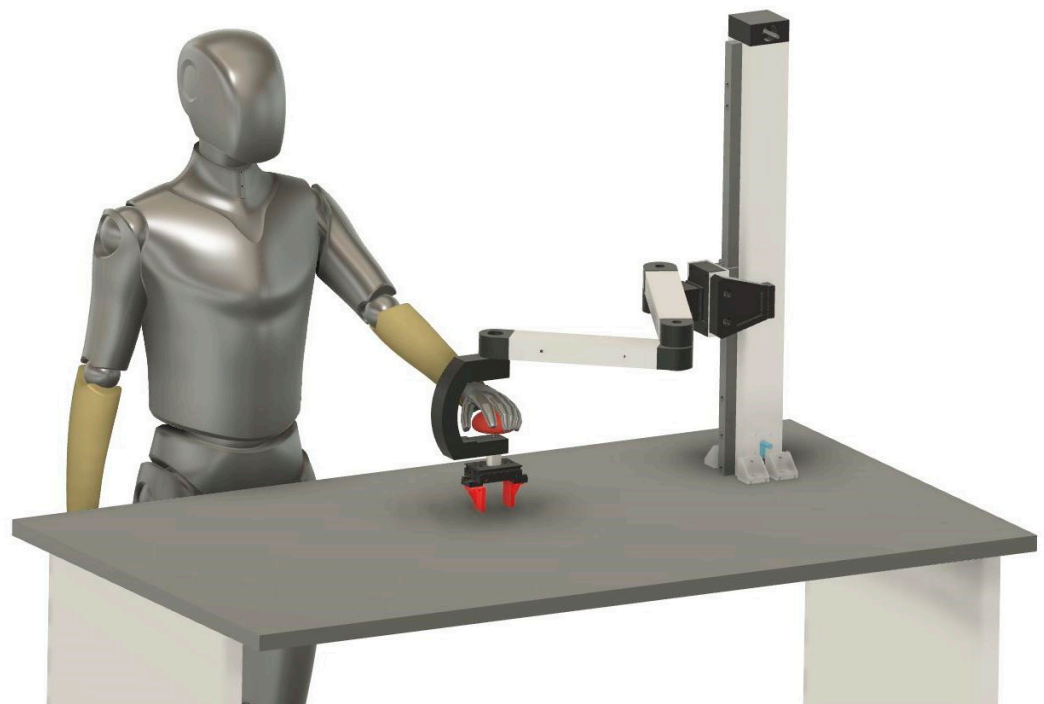


Figure 10. 3D CAD drawing of the proposed device.

The components other than the links of the arm and forearm are made of PLA+ by 3D printing. The links are made of an aluminum rectangular tube with a cross-section of $60 \text{ mm} \times 40 \text{ mm} \times 1.5 \text{ mm}$.

To verify the structural effectiveness of the machine, calculations by FEM were carried out. In Figure 11, the results of the calculations of the most proximal part of the shoulder joint are presented.

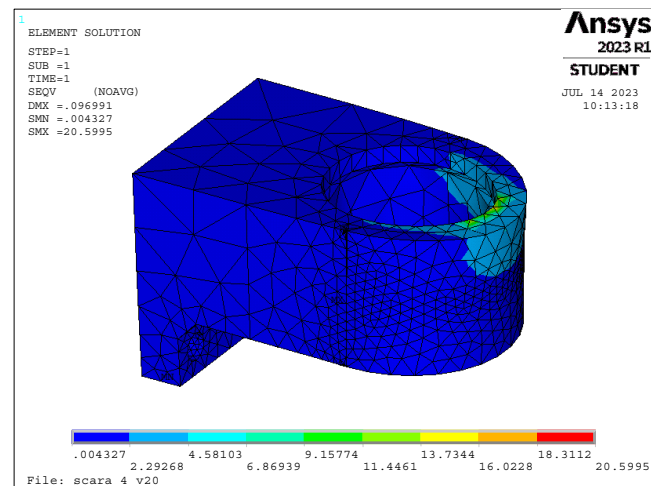


Figure 11. FEM for Von Mises stress calculation.

2.2. Control System

2.2.1. Electro-Mechanical Modeling, Control Strategy

Prior to building the prototype, we developed a model to validate the design and, in particular, the feasibility of the proposed control architecture relying on the drive's inner current (armature) regulation. Accordingly, a coupled model of the user–sensor–drive–actuation chain was formulated. In particular, a model of the arm of the utilizer, the load cell, the electric motor, the driver [50], the mechanical rotating and translating parts, and the transmission was considered.

The utilizer, by his hand, will apply a movement on the human machine interface (HMI), which is traduced in a force whose expression is:

$$F_o = k_u(z_r - z) + c_u(\dot{z}_r - \dot{z}) \quad (1)$$

where z_r is the reference position, defined in real time by the utilizer, z is the actual position, k_u is the stiffness of the utilizer arm, and c_u its viscous damping.

The HMI, due to the applied force, will produce a voltage:

$$V_c = F_o k_c \quad (2)$$

where k_c is the load cell characteristic. This voltage will be used to command the machine. It will be processed by an amplification algorithm, and the result will still be a voltage that is the input to the driver of the actuator. The simplest working algorithm will be a linear function (gain constant) applied to the load cell voltage:

$$V_d = V_c k_g \quad (3)$$

where k_g can be defined as a gain constant of the device.

The actuator (BLDC) electric motor, thanks to the appropriate conversion of its electric parameters, can be described by an equivalent DC electric motor (with single phase). This way, management of the governing equations is simplified. Given R_{BL} , L_{BL} , k_{EBL} , k_{TBL} , respectively, the phase resistance, the phase inductance, the phase back electromotive force, and the phase motor torque constants of the BLDC motor, the parameter values to be considered in the DC equivalent motor model are:

$$R = \frac{1}{2} R_{BL}, \quad L = \frac{3}{2} L_{BL}, \quad k_E = \sqrt{\frac{3}{2}} k_{EBL}, \quad k_T = \sqrt{\frac{3}{2}} k_{TBL}. \quad (4)$$

The driver is used to make a torque control. To do that, it implements a closed-loop control over the armature current of the motor. The governing equation of the DC motor equivalent to the BLDC motor is:

$$V_d = RI + \frac{dI}{dt}L + k_E \frac{d\theta}{dt} - V_{PI} \quad (5)$$

where V_{PI} is the feedback signal the driver uses to make the current I proportional to the control signal, V_d . Its expression, according to a proportional (P) control, is:

$$V_{PI} = k_{PI}(I_r - I) \quad (6)$$

where k_{PI} is the proportional constant for the current error and I_r is the current reference, whose expression is:

$$I_r = \frac{V_d}{R}. \quad (7)$$

On the mechanical side, from Figure 12, where the free body diagrams of the mechanical parts are shown, as for the rotating mass (rotor, pulleys, encoder), we have:

$$T_{out} = T_m - J_r \frac{d^2\theta}{dt^2} - c_r \frac{d\theta}{dt} \quad (8)$$

where T_{out} is the torque available as input to the transmission pulley, $T_m = k_T I$ is the electromagnetic torque, J_r is the inertia moment of the rotating mass, θ is the actual position of the rotor, and c_r is the rotational losses coefficient.

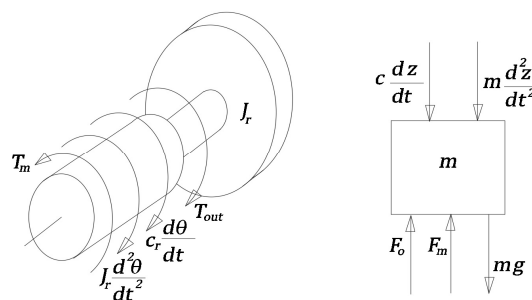


Figure 12. Free body diagrams of rotating and translating masses.

The force provided to the translating parts of the machine, by considering the pulley radius r and the efficiency of the belt transmission η , is:

$$F_m = \frac{T_{out}}{r} \eta. \quad (9)$$

Finally, the dynamic equation of the translating mass (carriage, arm, handle, gripper, and load) is:

$$m \frac{d^2z}{dt^2} + c \frac{dz}{dt} = F_o + F_m - mg \quad (10)$$

where m is the translating mass, c is the translating motion losses coefficient, and g is the gravity constant. To properly link equations, the following linear-to-rotating motion kinematic relations have to be considered:

$$\frac{d^2z}{dt^2} = \frac{d^2\theta}{dt^2} r, \quad \frac{dz}{dt} = \frac{d\theta}{dt} r. \quad (11)$$

The assistance law follows the human-in-the-loop force-sharing paradigm introduced in [51], but it is implemented here through an electric actuation chain. The handle-mounted

Overall, the simulations were stable for all tested inputs and confirmed the expected assistance behavior.

For example, Figure 14 on the left shows a simulation result in which a chirp movement was used as signal input compared to the movement performed by the device. It can be seen that the tracking ability is remarkable. The forces applied by the operator and machine for the same test are shown on the right.

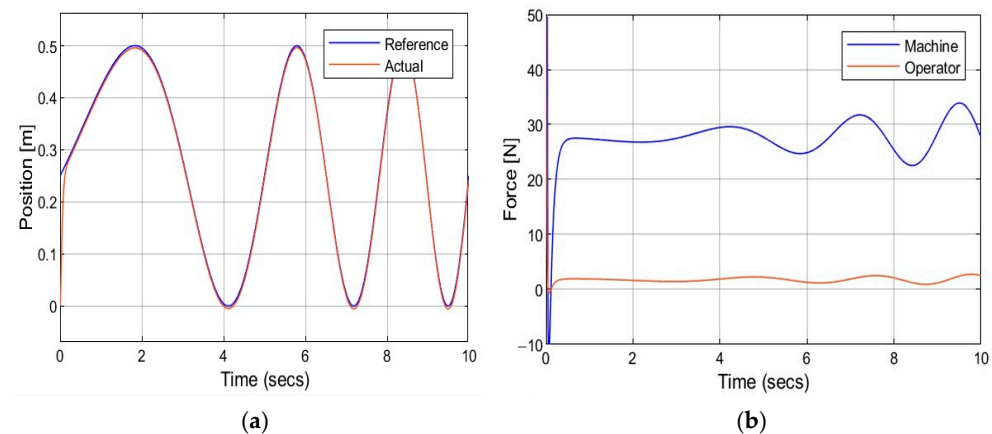


Figure 14. Numerical simulation: trajectory tracking (a), forces by the operator and machine (b). The input signal is a chirp type with a mean value of 0.25 m, amplitude of 0.25 m, and frequency from 0.1 Hz (initial) to 0.5 Hz (at target time of 10 s). The mass considered is 3 kg. It can be seen that the sum of the forces in the initial phase, in which the inertial loads are small, is about 30 N.

2.2.2. Hardware

The control system hardware consists of the microcontroller and the BLDC motor driver. The used microcontroller is a 32-bit based on the SAM3X8E ARM Cortex-M3 microcontroller (Atmel Corporation, San Jose, CA, USA). It has an 84 MHz clock and works at 3.3 V. It communicates via UART with the driver.

The driver is based on the STM32F405RG processor and TI DRV8301 gate drivers. It implements the Field Oriented Control (FOC) and can manage position, velocity, and torque control.

3. Results

3.1. Electro-Mechanical Model

The electro-mechanical model was tested and used to verify the effectiveness of the idea behind the project. Several simulations were carried out based on different input signals to the device. Signals like sine and chirp were used with different periods and amplitudes for different loads to move. The simulations show high precision in the task of tracking the trajectory reference given as input. The process is very stable, and the effort provided by the user is always the same percentage of the overall load. The ratio between the load to be moved by the user and the total load (machine + payload) is a fraction that can be set by the gain constant k_g . In Figure 14, the results of a representative tracking simulation of a chirp signal with a total load of 30 N are presented. In Figure 14a, the comparison between the reference trajectory and the real trajectory is presented: the error is imperceptible. In Figure 14b, the comparison is made between the effort provided by the machine and the one by the user.

It can be seen that in the initial part of the movement, in which the inertial load is negligible, the total load provided is about 30 N as expected, while the ratio between the effort by the user and that by the machine is 1/9, meaning the user feels 1/10th of the real load the machine provides a gain of 10.

3.2. The Realized Prototype

After the encouraging results of the model, the prototype was realized according to the design. All the mechanical and electrical components were mounted on the frame, and the wiring harness was routed.

The MCU used for control (SAM3X8E) was used to acquire the load-cell signal at the human–machine interface and to generate the command for the BLDC drive. The parts were assembled. Figure 15 presents the assembled prototype.

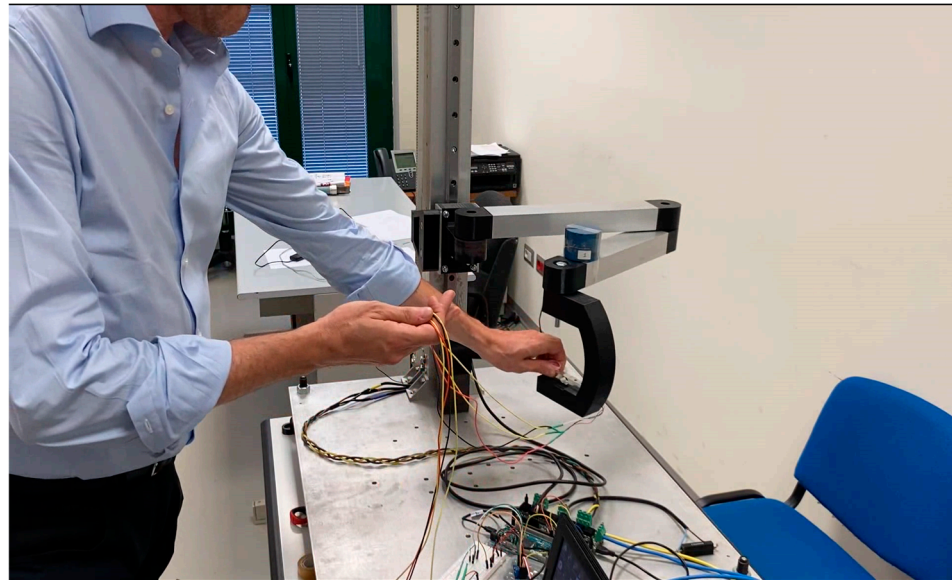


Figure 15. Realized prototype of the occupational assisting robot. The bench-top SCARA-like structure supports the user during vertical pick-and-place tasks by assisting the motorized prismatic joint (z-axis).

The drive, operating in field-oriented control with inner-loop current regulation, provided a torque proportional to the reference and therefore an assisting vertical force through the belt–pulley transmission.

A calibration procedure was performed to obtain (i) the conversion constant for the load cell (N per ADC count) and (ii) the force constant of the actuation chain (N per commanded current), by applying known masses and measuring the corresponding signals. These constants were then used in the amplification law so that the user would be required to provide only a preset fraction of the total load.

During operation, the user guides the handle along the task trajectory while the controller computes the motor current reference from the measured interaction force, thus supporting the load without requiring additional force sensors on the actuator side. This architecture keeps hardware complexity low while exploiting the driver’s built-in current feedback to deliver repeatable assisting forces.

3.3. First Experimental Test

In the experiment, the participant tracked the displayed position reference while the controller converted the measured interaction force into a motor-current command, thereby assisting the vertical motion according to the selected sharing ratio.

A first experimental campaign was carried out to verify the capability of the prototype to share the vertical load with the operator while preserving the operator’s ability to perform accurate pick-and-place motions.

Eight able-bodied participants (4 female, 4 male; age 27.5 ± 12.4 years; height 1.73 ± 0.09 m) were recruited for the test. All subjects provided informed consent.

Each participant was asked to move the vertical axis by gripping the handle and tracking a reference position signal displayed on a screen. Two loads were tested (0.5 kg and 1.5 kg) in addition to the moving mass of the device (≈ 3.5 kg). For each load, two reference signals were used: a shifted sinusoidal trajectory (offset 0.25 m, amplitude 0.25 m, 0.1 Hz) and a pseudo-random trajectory (bounded in [0, 0.5] m). Each condition was repeated twice: with the robot turned off (no assistance) and with the robot turned on (assistance enabled). In Figure 16, a participant is performing the tests.



Figure 16. The tests were carried out in front of a monitor. On the dynamic bar graph, the reference signal (red bar) and the signal of the actual position (blue bar). On the right, the signals of the forces produced by the participant and the machine.

This experimental campaign is intended as a pilot proof-of-concept study; therefore, no a priori power analysis was performed.

3.3.1. Data Acquisition and Signal Processing

The interaction force at the handle was measured by a strain-gauge load cell. The load-cell signal was conditioned and digitized by a HX711 24-bit ADC (output data rate selectable between 10 and 80 Hz) and acquired by the control MCU (SAM3X8E, 84 MHz). The same board read the motor current feedback from the drive and streamed both signals to a PC over serial (115200 baud) for logging using SerialPlot. The reference trajectory was generated on a second board (ATMega328), which, in the same loop, acquired the prismatic-joint position via a wire potentiometer and streamed both reference and measured position signals to the PC (115200 baud). Surface EMG of the bicep brachii was acquired using a MyoTrac™ device (Thought Technology Ltd., Montréal, QC, Canada) with a surface electrode (T3402) and a Myoscan preamplifier (SA9503M); the MyoTrac provides a conditioned analog output (0–2 V), which was sampled by Arduino Uno and logged on a dedicated PC via serial. No additional digital filtering was applied beyond the instrumentation's built-in conditioning; for each trial, the mean absolute tracking error (e_{med}), the mean force-sharing ratio $F(\%)$, and the mean EMG level were computed over the entire time series.

3.3.2. Statistical Analysis

Statistical comparisons between robot OFF and robot ON conditions were performed within subjects for each of the four task conditions (sinusoidal/random refer-

ence $\times 0.5/1.5$ kg load). Given the small sample size ($n = 8$), the Wilcoxon signed-rank test was used for the force contribution $F(\%)$ and for the tracking error e_{med} , while a paired t -test was used for the mean EMG level. All tests were two-sided, with a significance level $\alpha = 0.05$.

The tracking performance was quantified through the mean absolute tracking error, e_{med} , computed over the entire trial. The contribution of the operator was quantified as the percentage of the user force with respect to the total vertical force, $F(\%) = F_o / (F_o + F_m) \cdot 100$.

In addition, surface EMG of the bicep brachii was acquired during the trials using a MyoTrac™ (Thought Technology Ltd.), and its mean amplitude was used as an indicator of muscular effort. In Figure 17, the graph of a sinusoidal test with the machine activated, and the load of 0.5 kg is shown.

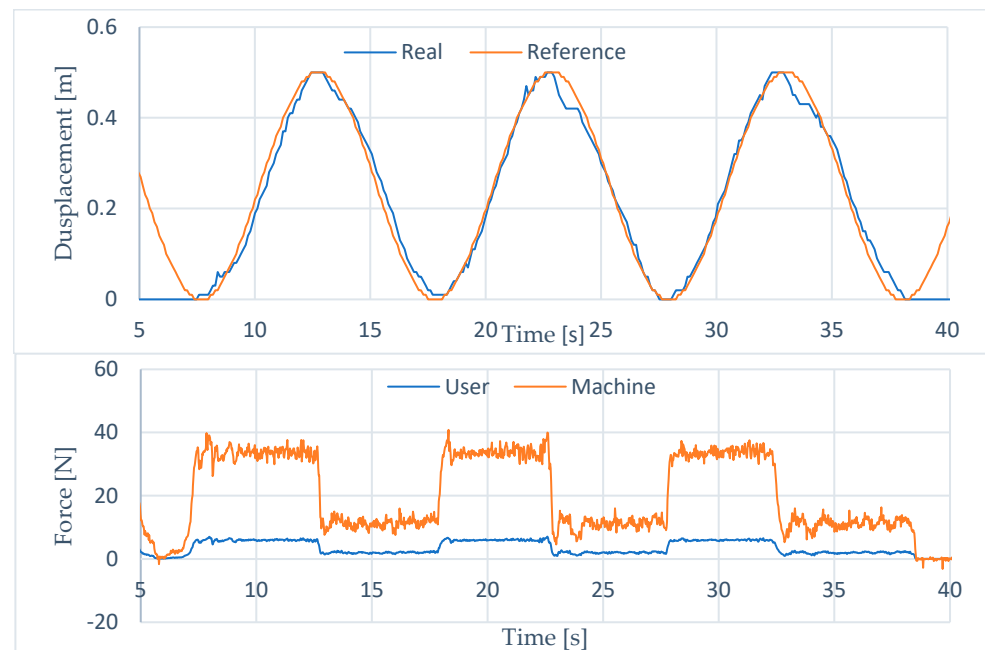


Figure 17. Graph of a typical position tracking test (top) and the related forces involved (bottom).

Overall, the robot provided a nearly constant force-sharing ratio across conditions: with assistance enabled, the user contributed about 15% of the total load (Table 2).

Table 2. Summary of the experimental results (mean $\pm$ SD across participants).

Ref. Signal	Load (kg)	F_o , Robot ON (%)	Δe_{med} (%)	EMG Reduction (%)
Sinusoidal	1.5	15.06 ± 0.16	12.1 ± 26.6	60.5 ± 15.1
Sinusoidal	0.5	15.10 ± 0.19	17.9 ± 21.1	57.0 ± 19.1
Random	1.5	15.02 ± 0.12	7.6 ± 9.0	62.4 ± 17.5
Random	0.5	14.96 ± 0.58	5.0 ± 6.4	62.9 ± 15.4

This reduction in user force contribution was statistically significant in all conditions (Wilcoxon signed-rank test, $p = 0.0078$). See Table 3 for the complete set of p -values.

Tracking accuracy improved in most conditions, with larger benefits for the sinusoidal task and smaller, more variable benefits for the random task (Figure 18). Muscular effort was consistently reduced, with an average EMG reduction of about 57–63% across loads and reference signals (Table 2 and Figure 19). A short usability questionnaire indicated low

perceived complexity and discomfort, and a clear perceived reduction in effort when the robot was active.

Table 3. Statistical comparison between robot OFF and ON conditions (within-subject p -values).

Condition	F_o p -Value (Wilcoxon)	e_{med} p -Value (Wilcoxon)	EMG p -Value (Paired t -Test)
Sinusoidal, 1.5 kg	0.0078	0.4609	1.61×10^{-4}
Sinusoidal, 0.5 kg	0.0078	0.0781	0.0015
Random, 1.5 kg	0.0078	0.0547	3.50×10^{-4}
Random, 0.5 kg	0.0078	0.5469	4.40×10^{-4}

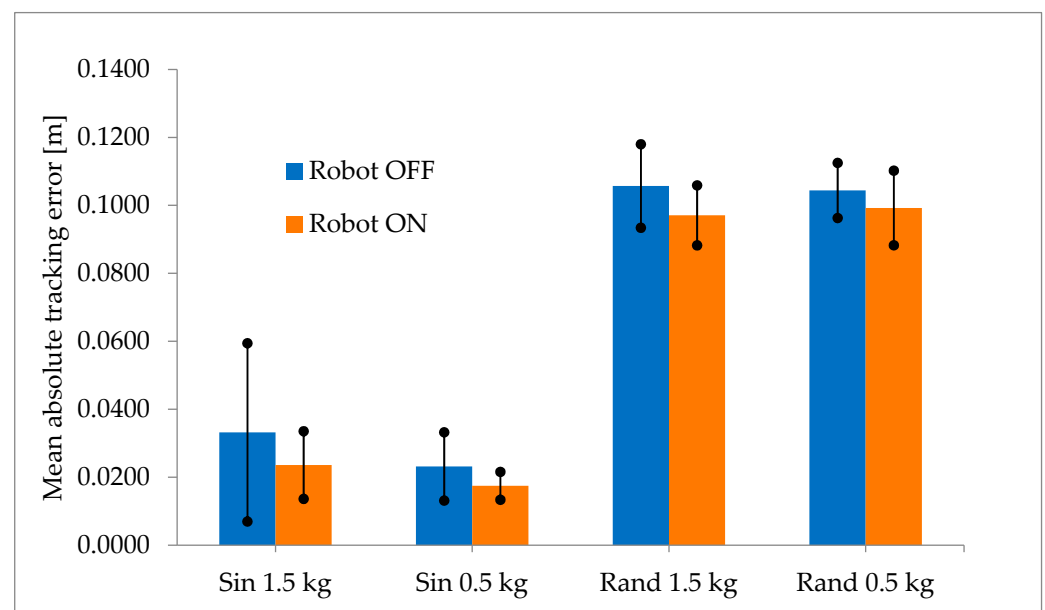


Figure 18. Mean tracking error (e_{med}) with robot OFF and robot ON for sinusoidal and random reference trajectories, with 1.5 kg and 0.5 kg loads. Error bars represent ± 1 SD.

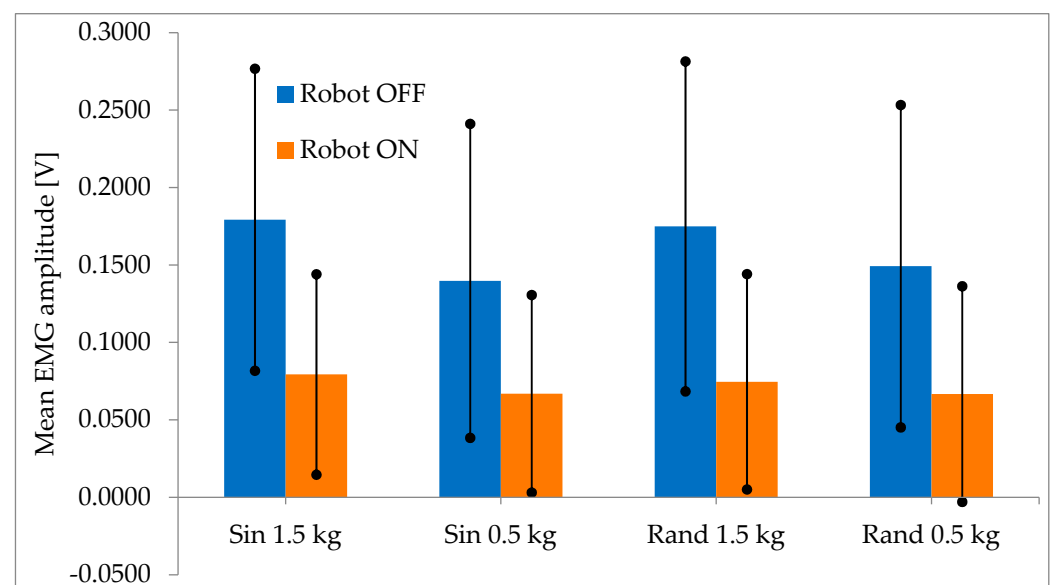


Figure 19. Mean EMG amplitude of the bicep brachii with robot OFF and robot ON for the same experimental conditions as Figure 16. Error bars represent ± 1 SD.

Changes in tracking error did not reach statistical significance in any condition (Wilcoxon signed-rank test, $p \geq 0.0547$), whereas the reduction in mean EMG level was statistically significant in all conditions (paired t -test, $p \leq 0.0015$). See Table 3 for the detailed results.

4. Discussion

The experimental results confirm that the proposed architecture can effectively implement force sharing in a simple way. By combining a single interaction-force sensor at the handle with a motor drive capable of accurate current (torque) control, the system delivered a nearly constant amplification level across tasks and loads, requiring the user to provide only about 15% of the total vertical force.

As for the relation to classical impedance/admittance control, a comparison is proposed in Table 4.

Table 4. Relation to classical impedance/admittance control.

Approach	Typical Sensing	Control Objective	Remarks/Limitations
This work (force-sharing via current control)	Single interaction-force sensor at handle; motor current feedback inside the drive	Prescribed force-sharing ratio for vertical load handling (user provides motion reference)	Very simple hardware/software; suited to vertical manipulation; does not regulate arbitrary 6-DoF contact forces
Impedance control (classical)	Robot position/velocity; often interaction force/torque at end-effector or joints	Impose a desired dynamic relation between motion and force (robot behaves like mass–spring–damper)	Requires model/tuning; typically needs both motion and force information; higher controller complexity
Admittance control (classical)	Interaction force/torque; robot position/velocity (commanded by an outer-loop admittance)	Generate motion from measured force through a virtual admittance (force-to-motion mapping)	Requires stable force measurement and compliant actuation; outer-loop dynamics must be tuned for safety

While impedance/admittance controllers typically implement an explicit outer-loop dynamics using both motion and force information, the proposed approach can be seen as a minimal force-sharing strategy for vertical manipulation: the user remains in charge of motion generation, and the robot contributes a calibrated fraction of the required vertical force through the current-controlled drive.

Besides load sharing, the prototype preserved—and in most cases improved—task execution accuracy. The sinusoidal tracking task benefited more from the assistance, whereas the pseudo-random trajectory produced smaller and more variable improvements, likely due to the higher cognitive demand and to the subject-dependent adaptation to the assisted dynamics. The consistent reduction in bicep EMG ($\approx 60\%$ on average) suggests that the robot can substantially reduce muscular effort and potentially delay fatigue during repetitive operations.

This first validation has limitations: the sample size was small and only able-bodied subjects were involved; the protocol focused on a single-axis vertical task; and only one muscle group was monitored. Future work will address broader occupational tasks, extended endurance trials, more comprehensive biomechanical measurements, and the integration of additional degrees of freedom and safety/ergonomic refinements to increase usability in real working scenarios. Accordingly, the present study should be considered exploratory/pilot, and no a priori power analysis was performed.

5. Conclusions

This paper presented the design and preliminary validation of a bench-top occupational assisting robot aimed at reducing biomechanical effort during repetitive vertical pick-and-place operations. The device uses a SCARA-like structure with passive planar joints and a motorized prismatic joint. A single load cell at the handle captures the operator's intention, while the motor drive provides repeatable assisting forces through current control, enabling a simple force-sharing strategy with limited hardware complexity.

In the first test with eight participants, the robot reduced the user's contribution to approximately 15% of the total load, decreased bicep EMG by about 60%, and generally improved tracking accuracy. Future work will focus on characterizing the operation of the entire working volume through an appropriate experimental setup with a three-dimensional tracking trajectory visualized with augmented reality; then on refining ergonomics and safety, and performing longer-term and task-representative experimental validations.

Funding: No external funding was received for this work.

Informed Consent Statement: Written informed consent was obtained from all participants.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the author.

Acknowledgments: The authors would like to acknowledge the support given by Leonardo Bianchi and Maria Elena Ciammola for their contribution to the experimental activity.

Conflicts of Interest: The author declares no competing interests.

Appendix A. Kinematic Models and Jacobian (Supplementary Derivations)

Appendix A.1

For the determination of the working volume, the direct kinematic model was considered. Using the modified Denavit–Hartenberg notation, the transformation matrix between the reference frame of the end effector with respect to the base is given by the product of all the single transformation matrices between link i and link $i - 1$:

$${}^0\mathbf{T}_E = {}^0\mathbf{T}_1 \cdot {}^1\mathbf{T}_2 \cdot {}^2\mathbf{T}_3 \cdot {}^3\mathbf{T}_4 \cdot {}^4\mathbf{T}_E \quad (\text{A1})$$

where, in the considered case of modified Denavit–Hartenberg notation,

$${}^{i-1}\mathbf{T}_i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & a_{i-1} \\ \sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -\sin \alpha_{i-1} d_i \\ \sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & \cos \alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (\text{A2})$$

Considering Figure 2, the numerical values of the parameters are shown in Table 1.

A reference for the end effector, E, was considered, which is rigidly connected with the handle with the origin in the attachment point of the gripper.

By the matrix in (A1), it is possible to determine the coordinates, with respect to the base, of any point, known as its coordinates with respect to the local reference of the handle frame, for any set of joint parameter values. By considering the position of the origin of the gripper frame in local coordinates ($p = [0 \ 0 \ 0 \ 1]^T$) and by varying the parameters of the joints in the respective definition domains, the working volume of the device is determined. In Figure 3, the working volume is presented, with variations of 20° for θ_i and 58 mm for

d_1 , obtaining 1287 different positions. The obtained point cloud was processed to show the working volume.

Appendix A.2

The core of the inverse kinematic model concerns the planar part of the robot, since for the vertical movement, the joint space corresponds to the Cartesian space. Although the rotational joints are not actuated, the inverse kinematic model can be useful for future developments of the device, that could include the possibility for the arm to be at constant height and to use a cable for the vertical motion from the tip of the robot, and to motorize the rotational joints for an automated tracking of the hand of the utilizer, based on a vision system. So, the inverse kinematic problem is formulated and solved as follows.

The position of the end effector in the base reference is given by (Figure 2):

$$\begin{cases} x_E = a_1 + a_2 \cdot \cos\theta_2 + a_3 \cdot \cos(\theta_2 + \theta_3) \\ y_E = a_2 \cdot \sin\theta_2 + a_3 \cdot \sin(\theta_2 + \theta_3) \\ z_E = d_1 - d_5 \end{cases} \quad (\text{A3})$$

We consider the first two Equations in (A3), move a_1 to the other side of the equality sign, square both sides, and sum. We have:

$$(x_E - a_1)^2 + y_E^2 = a_2^2 + a_3^2 + 2a_2a_3 \cdot \cos\theta_3 \quad (\text{A4})$$

from which yields:

$$\theta_3 = \pm \arccos \left[\frac{(x_E - a_1)^2 + y_E^2 - a_2^2 - a_3^2}{2a_2a_3} \right] \quad (\text{A5})$$

From Figure 4 we have:

$$\theta_2 - \phi = \arctan \left(\frac{y_E}{x_E - a_1} \right) \quad (\text{A6})$$

$$\phi = \pm \arccos \left[\frac{(x_E - a_1)^2 + y_E^2 + a_2^2 - a_3^2}{2a_2 \sqrt{(x_E - a_1)^2 + y_E^2}} \right] \quad (\text{A7})$$

thus yielding:

$$\theta_2 = \arctan \left(\frac{y_E}{x_E - a_1} \right) \pm \arccos \left[\frac{(x_E - a_1)^2 + y_E^2 + a_2^2 - a_3^2}{2a_2 \sqrt{(x_E - a_1)^2 + y_E^2}} \right] \quad (\text{A8})$$

As for the prismatic joint, we have:

$$d_1 = z_E - d_5 \quad (\text{A9})$$

Appendix A.3

In the present case, the angular joints are not actuated. Still, the singularity analysis is of interest since the movement of the robot can be locked during the operativity and this has to be avoided. It is easy to argue that when the forearm of the robot is aligned with the arm, radial movements in the Cartesian space are not possible. In this section, the Jacobian of the robot is derived to carry out a singularity analysis and provide quantitative evidence that the risk can occur during the operativity with the robot.

By the time derivative of Equation (A3), we obtain the end effector velocity:

$$v_E = \begin{bmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{bmatrix} = [J(\theta_2, \theta_3)] \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{d}_1 \end{bmatrix} \quad (\text{A10})$$

where:

$$J(\theta_2, \theta_3) = \begin{bmatrix} -a_2 \cdot \sin \theta_2 - a_3 \cdot \sin(\theta_2 + \theta_3) & -a_3 \cdot \sin(\theta_2 + \theta_3) & 0 \\ +a_2 \cdot \cos \theta_2 + a_3 \cdot \cos(\theta_2 + \theta_3) & +a_3 \cdot \cos(\theta_2 + \theta_3) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{A11})$$

is the Jacobian matrix. We have:

$$\det(J) = a_2 \cdot a_3 \cdot \sin \theta_3 \quad (\text{A12})$$

Singularity conditions occur when $\det(J) = 0$; this is when $\theta_3 = 0$, or $\theta_3 = \pi$. Getting closer to these conditions, the needed joint velocities tend to have infinite values. To have a map of the singularities, a study of Equation (A12) was carried out, and the results are shown in the graph in Figure 5.

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