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Article

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Bionic Arms with Hand Dominance to Enable Division of Labor for Bilateral Amputees

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Abstract

Bilateral amputees retain a sense of hand dominance; even after amputation, they still prefer the dominant hand over the non-dominant to perform their daily tasks/duties. This aspect of hand dominance has not been explicitly accounted for in any commercially available prostheses. In modern prostheses, both arms are treated as a single unit and end with the same mechanical design, without any change in degrees of freedom, which conflicts with the well-established neuro-motor division of labour between dominant and non-dominant limbs, and the design space of bilateral bionic systems remains undressed. Therefore, systematic design contributions to this area represent a novel engineering advance. To address this gap, this work proposes a conceptual and engineering design framework for bilateral prosthetics grounded in the asymmetric roles of the dominant and non-dominant hemispheres. The framework is actualised for a left-hand-dominant bilateral amputee as a proof-of-concept. The proof-of-concept prototype is evaluated through benchtop validation, confirming that each arm

fulfils its intended asymmetric functional roles. The results establish the technical feasibility of the design framework and provide a foundational step towards the possibility of reducing the cognitive burden and enabling more intuitive bilateral prosthetic use in future user-centred investigations

Keywords: division of labour(dol), hand dominance, design framework, degrees of freedom(dof), rehabilitation, asymmetrical bilateral prosthetics

1 Introduction

Amputations are a significant global public health concern, with serious consequences for individual well-being and social expenses. According to the World Health Organisation (WHO), approximately 10 million individuals worldwide live with arm amputations, and the majority of them reside in developing countries. An estimated 1.6 million Americans lost a limb in 2005; by 2050, that number is expected to more than double, eventually impacting over one in 120 individuals. Similarly, in Europe, it was reported that there were an estimated 1900 traumatic upper limb amputations in 2010. [1–3] Amputation of a hand or arm constitutes a severe physical and psychological trauma affecting the patient's autonomy, self-image and daily functioning. Traumatic accidents are the leading causes of upper limb amputations; the impact of arm amputation is very severe because the upper extremities serve as instruments/tools for communication, sexuality, affection, aggression, and employability. [4, 5]
We here focus on bilateral amputees, which means those who have lost both of their arms; most bilateral amputees have some degree of hand dominance before amputation, unlike those with natural-born disabilities, and using prosthetics that are not made to fit them would make them feel disconnected. Arm dominance, often called handedness, is the preference for one hand over the other for performing certain tasks in daily life. Humans' inherent arm dominance enables them to perform daily activities with a division of labour that facilitates efficient cognitive utilisation. One is the dominant hand, while the other is the non-dominant hand. A person with a dominant hand preference typically uses their dominant hand for activities of daily living (ADLs). [6]
This meaningful difference exceeds simple preference; the dominant arm consistently demonstrates superior skill and control during complex manual tasks, while the non-dominant arm supports bimanual tasks.[7] A clear division of tasks in our natural human biomechanics depicts the difference between dominant and non-dominant arms, serving distinct purposes. The dominant arm functional profile has innate qualities that enable it to perform tasks with greater dexterity and speed that require fine motor control, such as manipulating tools and holding a key. Conversely, although often considered "inferior" or less subjectively preferred, non-dominant arms(N.D Arm) demonstrate stabilisation and bimanual coordination as distinctive functional profiles. The non-dominant arm(D Arm) excels at tasks requiring sustained force, providing a strong foundation for the dominant arm to execute complex movements. [8–11]
This division of labour between both arms emphasises their complementary nature. Worldwide, almost 90% of people prefer to use their right hand, which is developed

at a very young age. [12] Approximately only 10 per cent of the population is left-handed. Approximately 1 per cent of individuals show no hand preference, indicating ambidexterity. [13] According to studies, persons who frequently use their left dominant arm for a variety of chores are more likely to sustain job-related injuries, which has a risk factor 4.9 times higher than that of people who use their right arm. The above indicates that left-arm amputations may be more prevalent in home and work environments because the world primarily prioritises workplaces for right-handed individuals, thereby underscoring the lesser-observed left-handed population.[14, 15] It highlights the importance of developing innovative prosthetic solutions to address the needs of those who have lost the use of both arms, particularly for bilateral amputees with the left arm as their dominant one; the design of the readily available prosthetic fails to incorporate the hand dominance aspect which makes it more challenging for the left arm dominant amputees to accommodate to a prosthetic which does not suit their preference. For an individual who has lost their dominant left hand, the challenges extend beyond the physical in daily life. The sudden loss of motor control in the preferred limb disrupts their self-identity both emotionally and psychologically, leading to isolation, depression and a diminished sense of independence. [16, 17]
Apart from highlighting the importance of the division of labour in prosthetics, this underserved population requires a prosthetic design approach that accounts for the asymmetric neuromotor roles of each limb,[10, 18] an approach that is not yet adopted by research or commercial prosthetics. I-limb, Open Bionic, Bebionic, and Hannes Hand are some commercially available and research-level bionic prosthetics that feature sophisticated capabilities, including fingers with multiple degrees of freedom, multiple grip patterns, and myoelectric control.[19] These devices enable users to perform daily activities with high dexterity and greater flexibility than most basic prosthetics.[20] However, using these multifunctional devices with symmetric design that do not reflect natural bimanual coordination relies heavily on visual feedback, and the user must consciously monitor and plan, adjusting the grip modes as needed. Over time, the demand for complex tasks may increase, which could contribute to increased cognitive fatigue and reduced usage among users. There are many commercially available devices with advanced functionality and control algorithms, as well as prosthetic devices with restored sensory feedback [21]. However, they do not account for hand dominance/handedness, which plays a crucial role in determining natural human motor control, behaviour, and task accomplishment. For example, the Ottobock sensor hand speed, which is an effective solution for unilateral users, enables single-axis open-and-close actuation with no wrist articulation and adaptive finger compliance.[22] For a non-dominant prosthetic role in the bilateral system, the prosthetic should be able to orient objects via pronation and supination and conform to irregular shapes through a compliant grasp for stabilisation during dominant-arm manipulation. A comprehensive overview of existing prosthetic solutions confirms that such functional requirements, addressing the hand-dominance paradigm, are not part of the design in any existing prosthetic solutions.[23, 24] As a result, current prosthetic technologies with functional sophistication may not fully replicate the intuitive ease and functional asymmetry of natural bilateral hand use.
Apart from this functional gap, the design space of bilateral bionic arms itself is

largely unexplored in current prosthetics research. The available prosthetic solutions are focused on addressing unilateral amputation, and this same methodology is proposed for bilateral amputees without considering their motor lateralisation and functional roles. Therefore, to address this gap, any principled engineering contribution to this field constitutes a significant advancement in an area with limited underlying knowledge. In this work, we try to address this gap by proposing a conceptual and engineering design framework for bilateral prosthetics grounded in the asymmetric roles of the dominant and non-dominant hemispheres. The framework is actualised for a left-hand-dominant bilateral amputee as a proof-of-concept for whom no dominance-aware prosthetic design methodology currently exists in either commercial or research prosthetics, and its design detail is described in Section 3. This work makes two contributions. The first contribution is the proposed conceptual and engineering design framework for asymmetrical bilateral prosthetics based on hand dominance that links the functionally required roles of each arm to their mechanical design parameters, producing a system whose overall complexity is distributed according to hand-dominance role rather than applied uniformly to both arms. The second contribution is the proof-of-concept prototype for the left-hand-dominant amputee scenario with differentiated degrees of freedom and design complexity for both bionic prototypes based on hand-dominance to facilitate natural division of labour. The clinical validation of the asymmetric bilateral prosthesis is beyond the scope of this study. At the same time, the results from the bench-top evaluation establish the technical feasibility of the design framework and provide a foundational step towards the possibility of reducing the cognitive burden and enabling more intuitive bilateral prosthetic use in future user-centred investigations.

2 Results

The following bench-top evaluations demonstrate the functional capabilities of each prosthetic arm through task-level assessments that illustrate complementary functionality between the dominant and non-dominant bionic arms.

2.1 Structure of a bionic arm

2.1.1 Dominant left bionic arm

The dominant bioinc arms design achieved considerable robustness and rigidity. The key design feature was that we directly connected the linear actuator to the fingers via a four-bar linkage, eliminating the need for a tendon-based approach that employs fishing line and servos. With this method, we ensured positional consistency of the fingers throughout the bionic arms' articulation. As depicted in the Figure 1, we can see that the fully articulated digital positions of the fingertips (distal phalanges) remain parallel to the palm, exhibiting anatomical precision. To achieve this, precise alignment was an integral design element of the dominant left bionic arm. It demonstrates that the dominant left bionic arm can be articulated in a smooth and controlled manner to achieve the high positional accuracy required for fine motor skills, such as performing

intricate articulation or grasping delicate objects.
The wrist of the bionic arm was very robust and sturdy, considering that the entire hand weight was supported by a spherical joint with four actuators acting as stabilizers. The wrist range of motion functioned as intended, performing simultaneous flexion and radial/ulnar deviations. Furthermore, the wrist's rotational motion functioned well, as the ball bearings efficiently distributed the weight and forces on the swivel to the forearm. The complete assembly of the dominant left bionic arm is shown in Figure 2.



Fig. 1 Fine control of dominant left arm: The side view of the hand with complete assembly of parts in the palm depicts the maximum range of finger closure in a clenched fist, excluding the thumb.

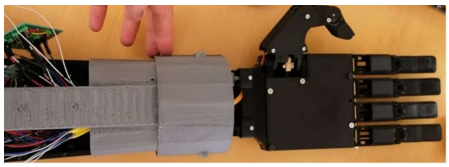


Fig. 2 3D printed prosthetic hand: Final 3D printed dominant left bionic arm.

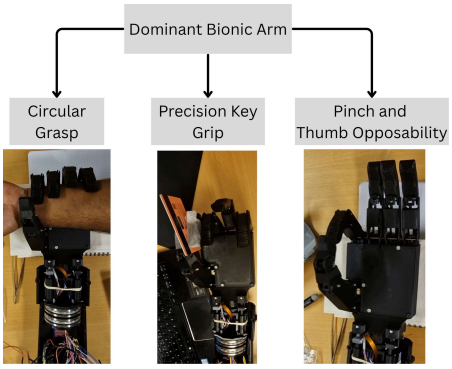


Fig. 3 Grasp capability of dominant left bionic arm: The dominant left bionic arm exhibits several grip patterns showcasing multiple degrees of freedom, mimicking natural human biomechanics.

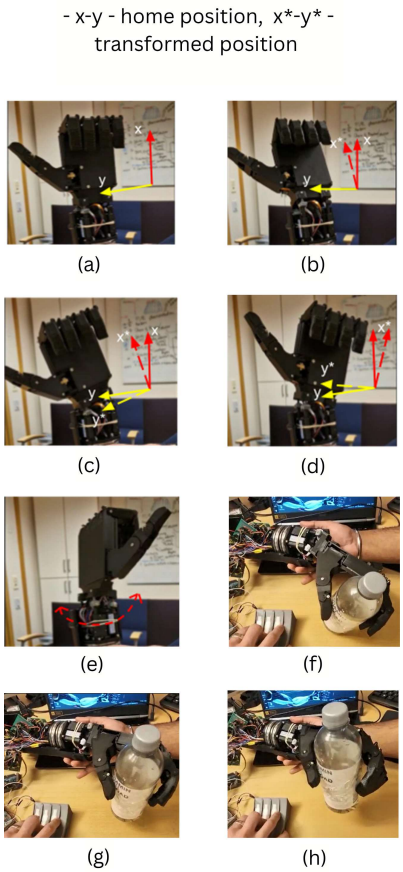


Fig. 4 Wrist mobility of wholly assembled dominant left bionic arm: (a) steady position of the bionic arm, (b) radial deviation of the bionic arm, (c) Ulnar deviation of the bionic arm, (d) Extension of the wrist, (e). Rotation of the wrist is facilitated by the ball-and-socket joint and ball bearings (f), (g), and (h). This illustrates the simultaneous actuation of multiple degrees of freedom during the performance of a typical daily task.

2.1.2 Non-dominant right bionic arm

The non-dominant bionic arm design employs an artificial tendon-based approach for finger actuation, rather than a four-bar linkage system. We have utilized high-end non-braided fishing lines for their non-stretching properties. These lines connect to the fingers and are tensioned by servo motors attached to the forearm of the bionic arm. Individual servo motors control all fingers, with guide holes incorporated into the fingers design to optimize tendon orientation and prevent snagging. The significant advantage of the tendon actuation is the joint conformity, which means the fingers adapt to the shape of the grasped objects. This feature of the non-dominant right bionic arm excels in performing tasks that require adaptive movements, such as picking up irregularly shaped objects and stabilizing them in place. The wrist of the bionic arm

allows for 180 degrees of rotation, similar to a human wrist, but lacks the functionality of flexion and extension, limiting its overall dexterity.

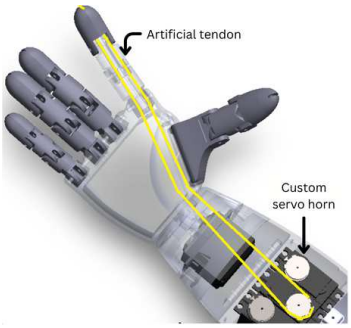


Fig. 5 Drive system of the non-dominant right arm: Depiction of the tendon actuation system for the index finger. When the servo horns rotate, they tighten the artificial tendons, which move the fingers.

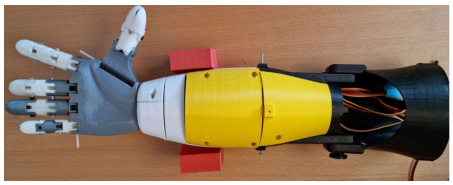


Fig. 6 3D printed prosthetic hand: Final 3D printed non-dominant right bionic arm.

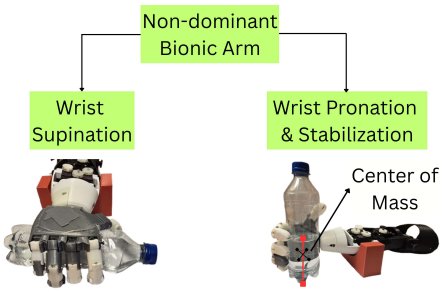


Fig. 7 Grasp and wrist mobility of wholly assembled non-dominant right bionic arm: The image demonstrates efficient manipulation of dynamic load with shifting mass, i.e, half-filled water bottle. The bionic arm attempts to grasp the water bottle near the center of mass, performing pronation and supination (wrist rotation) with minimal torque. This approach ensures effective and stable lift, mimicking the natural and efficient strategy that humans would use for such a task.

2.2 Bionic Arm Functional Validation: Complementary Role Demonstration of Non-Dominant and Dominant Arms

We conducted bench-top functional validation for the developed proof-of-concept prototype to assess whether each arm fulfils the assigned functional roles specified by the framework, precision-oriented performance for the dominant arm and stabilisation-oriented performance for the non-dominant arm. The assessments demonstrated that the straightened fingertip of the non-dominant right bionic arm is capable of supporting approximately 70 grams (0.7 Newtons) of force. It was also observed that the finger's load-bearing capacity was dynamic and it changes as the finger bends for grasping an object. That means that if the fingertip moves towards the palm, it results in a higher force output due to the reduced distance between the knuckle and the point of application. Under typical operating conditions, the entire bionic arm assembly can lift or sustain up to 600 grams. Additionally, we observed the actuation behavior of the elbow joint, and it achieved a flexion range of up to 110 degrees. The wrists' 180-degree rotation capability ensured effective lifting of objects with dynamic masses, while simultaneously providing the needed stabilization. In the dominant left bionic arm, the assessments revealed that each finger has a lifting capacity of approximately 150 grams. And the fingers had a consistent motion path even after repeating the same action many times. This was made possible by the four-bar linkage mechanism and linear actuator, without the use of a PID regulator; the wrist was able to exhibit higher dexterity with a natural range of motion similar to that of a human wrist. This was possible because the linear actuators could be fine-tuned to perform precise and smooth actuation, thereby the wrist offered superior task consistency in comparison to the non-dominant bionic arm.

The collective results from the bench-top evaluation were consistent with framework rule predictions for dominant and non-dominant arms as mentioned in Table1, demonstrating the technical feasibility of the proposed framework and providing a foundation step towards the possibility of reducing the cognitive burden and enabling more intuitive use; the real-world outcomes are to be explored in future user-centred investigations.

To provide a better understanding of the functional validation and mechanical integrity of our proposed solutions, we have included a comparative analysis of readily available arms on the market in Table 1, in which, notably, no existing commercial or research prosthetic system has this bilateral approach towards asymmetric role-differentiated specification for their prosthetic design, this highlights the novelty of the proposed engineering framework in this work.

Table 1 Bionic Arms Features Comparison: Side-by-side comparison of our proposed bilateral solution vs. three advanced commercial prostheses. Differences in motion range, grasp control, lifting ability, and design complexity underscore how our dominance-based solution strikes a balance between performance, accessibility, and user comfort.[25],[26],[27]

	This Work		Hannes Hand	Open Bionics	BeBionic
Features	N.D Arm	D Arm			
Independent Finger Movement	Yes	Yes	Yes	Yes	No
Pronation / Supination (deg.)	0–180	0–180	0–180	0–180	0–180
Wrist Flexion / Extension (deg.)	No	±50	±70	—	±30
Grasp	Standard	Advanced	Advanced	Advanced	Advanced
Thumb Opposability	Basic	Advanced	Advanced	Advanced	Advanced
Single Finger Lifting Capacity (kg)	0.15	0.55	—	—	6
Total Arm Lifting Capacity (kg)	0.6	2	—	13	45
Arm Dominance (Division of Labor)	Present	Present	—	—	—
Mechanical Design Complexity	Low	Low	High	High	High
Cost	Inexpensive	Inexpensive	Expensive	Affordable	Expensive

3 Methods

3.1 Design Framework for Hand Dominance-Based Asymmetric Bilateral Prosthetics

3.2 Rationale for Dominance-assistive Role Allocation

To the best of our knowledge, no established design methodology exists for prosthetic systems for bilateral amputees that accounts for the functional roles of the dominant and non-dominant limbs in line with the asymmetric principle of hand dominance. In the absence of an established framework for asymmetric bilateral design conventions, the proposed engineering framework in this work is based on a literature review of the dynamic dominance hypothesis of motor lateralisation.[10] This model proposes that different hemispheres of the brain control dominant and non-dominant actuation mechanisms, and that this differentiation should not be seen as stronger or weaker, but rather as specialised for two fundamentally different actuation mechanisms.The dominant arm primarily relies on predictive and feedforward control mechanism; these mechanism control the internal limb dynamics to plan and execute smooth multi-joint trajectories efficiently before movement begins.[10, 28, 29]While the non-dominant arm uses impedance control, in which the proprioceptive feedback

along with joint stiffness of the arm are altered reactively to achieve or maintain a stable final position despite any external disturbances.[10, 11, 30] This division in humans is supported by behavioural evidence, where the dominant arm demonstrates a higher level of trajectory planning and executes it efficiently during reaching and manipulation tasks; whereas the non-dominant arm demonstrates higher position stability and load compensation despite external disturbances.This interdependency between the arms supporting the division of labour is observed in everyday bimanual activity.[18] Our proposed framework utilises this established model as the theoretical foundation for deriving the functional requirements and mechanical design parameters for each prosthetic arm.

Table 2 Framework application logic for dominance-based asymmetric bilateral prosthetic design. Each rule maps a design parameter to its dominant-side and non-dominant-side specification, derived from the Dynamic Dominance Hypothesis [10, 11, 28–30].

Rule	Design Parameter	Dominant-Side Specification	Non-Dominant-Side Specification
1	DoF Allocation	High DoF sufficient to support all precision grip configurations the task profile demands; each digit actuated independently.	Low DoF only where stabilisation independently requires control; remaining digits grouped into shared synergy channels.
2	Actuation Mechanism	Rigid, geometrically constrained mechanism; trajectory must be deterministic and repeatable regardless of external load; actuators prioritise positional accuracy.	Compliant mechanism, joint stiffness modulates passively in response to external load; actuators prioritise torque and sustained load capacity over positional precision.
3	Wrist Configuration	Multi-axis must articulate across multiple planes simultaneously to support the full range of precision manipulation orientations.	Single-axis: one rotational axis sufficient to orient a held object in support of the dominant arm; additional axes add complexity without functional benefit.
4	Material Selection	Prioritise stiffness and dimensional stability; rigid components maintain linkage geometry under repeated loading cycles.	Prioritise low weight and compliance; lighter construction reduces fatigue during sustained stabilisation holds.

3.3 Framework-Derived Design Specification for Dominant and Non-dominant Arms

As discussed in the introduction, we are trying to address the underserved population of upper-limb bilateral amputees whose dominant hand before amputation was their left hand. For this particular group of people, there is no existing prosthetic

system that accounts for their innate motor lateralisation, as discussed in section 2.1 of the theoretical framework. Framework rules presented in Table 2 are not case-specific; they constrain the design space for any bilateral amputee prosthetic system by addressing hand dominance to enhance the natural division of labour. For our case of a left-hand-dominant amputee, the framework's application rules are applied to derive the following mechanical specification. The dominant left bionic arm design should be able to support the predictive trajectory-control demands of the dominant hemisphere system. All five fingers require independent actuation, and each finger is segmented into phalanges to enable multiple precision grip configurations such as key grip, lateral pinch and circular grasp. At the wrist level, the dominant left bionic arm needs five degrees of freedom, which consist of radial/ulnar deviation, rotation and flexion/extension of the wrist, to support a full range of dynamic motion to mimic the natural movements of the human wrist. The finger actuation mechanism chosen for the dominant arm was a four-bar linkage, as its design limits motion to produce deterministic movements with a repeatable trajectory despite external loads; this is an important mechanical design parameter for supporting dominant arm predictive control methods. The non-dominant right bionic arm design should support the impedance control demands of a non-dominant hemisphere system. At the finger level, the hand of the non-dominant bionic arm requires five degrees of freedom to grasp and stabilise objects of different geometries efficiently. At the wrist level, the non-dominant right bionic arm needs one degree of freedom, which is pronation and supination, to orient the grasped object and support dominant-arm manipulation tasks. A tendon-driven mechanism is chosen for the non-dominant right bionic arm's finger actuation, particularly because the tendon compliance naturally adjusts its phalangeal joint stiffness in response to external stimulation or disturbances, supporting the impedance control behaviour mechanism. Therefore, the dominant left bionic arm is assigned 11 DoF, and the non-dominant right bionic arm is assigned 6 DoF as per the framework design rules. The conceptual engineering framework solution is depicted in Figure 8.

4 Mechanical Design

The design process for the bionic arms began with a literature review of the neuromotor specialisation of the dominant and non-dominant arms, which informed the functional requirements for each prosthetic arm design and helped us to determine the required degrees of freedom, actuation mechanisms, and design complexity. The mechanical design described in this section is based on the proof-of-concept prototype for the left-hand-dominant case presented in Section 2.2, with each design specification following the application-framework logic in Table 2.

4.1 Wrist Kinematics and Actuation Mathematics

4.1.1 Mathematical Representation of Wrist Movement (Non-dominant right bionic arm)

The wrist of the non-dominant right bionic arm was directly attached to the servo motor gear using a press-fit mechanism. This mechanism can perform only pronation

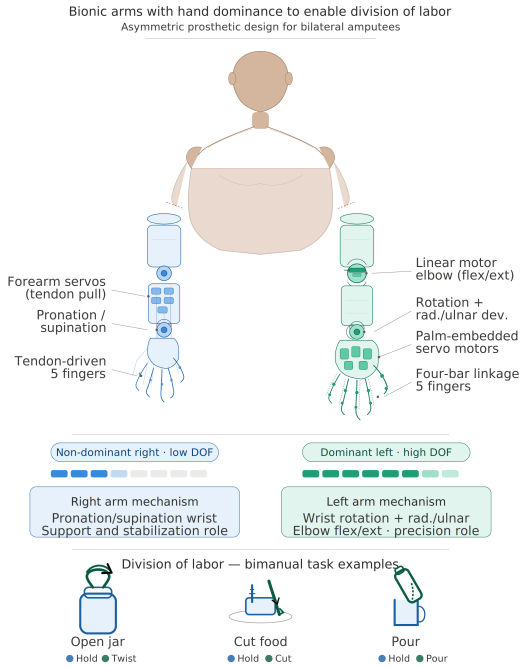


Fig. 8 Design Framework for Asymmetric Bilateral Prosthetics: Conceptual overview of the proposed bilateral bionic arm system with an asymmetric hand dominance design derived from the proposed framework.

and supination motion and rotates around the forearm longitudinal axis (z-axis in standard anatomical position). In a 2d plane

The motion is defined as:

$$x = r\cos(\theta); \quad y = r\sin(\theta); \quad z = z_0 \tag{1}$$

Where:

- r – radius of the wrist joint
- θ – rotation angle (limited to $\pm 90°$)
- z_0 – fixed height of the wrist along the z-axis

4.1.2 Mathematical representation of Wrist movement (Dominant left bionic arm)

Four linear actuators operate the wrist of the dominant left bionic arm; each linear actuator must move in sync with every slight movement to maintain the strength and position of the wrist. If synchronization is not maintained, the hand would lose contact with the arm, and the weight would shift to the actuators, leading to stress and possibly damage to the actuators. We developed a system to enable the actuators to operate in a synchronized manner. Four linear actuators were positioned at the corners of the rectangular surrounding wrist, which encased the central part of the

wrist that contained the ball joint as represented in Figure 10. The ball joint could slide smoothly within the bowl without any significant problems. The wrist motion can be simplified into two directions: the first movement is from side to side (radial and ulnar motion), and the second is from front to back(flexion and extension). In addition to the rotation of the wrist, the dominant left bionic arm has 3 degrees of freedom (DOF). To flex or bend in either actuation, the actuators must work in pairs. For instance, if the actuators were supposed to bend on the left side, two actuators on the left side had to retract the same amount. In comparison, the two actuators on the right side had to extend the same amount as they retracted to maintain the position and strength of the wrist. The principle stays the same for flexion and extension of the wrist. Two actuators in the front had to retract, and two actuators in the back had to extend the same amount as they retracted. We created a system of equations and conditions that allow the wrist to flex and bend sideways simultaneously. The area inside the rectangle is divided into four equal parts with actors in each corner. For instance, if the hand was supposed to incline towards actuator 1 (lower left corner, see Figure10). In this instance, actuators 1 and 3 had to retract, while actuators 3 and 4 had to extend to create a bend to the left. Actuators 1 and 2 had to retract, and actuators 3 and 4 had to extend to make the forward flex movement. This section of movement is designated as scenario 1.

The maximum extension length of the actuator is 20mm. For the wrist to move in all directions, the actuators need to have a base position that allows them to retract and extend simultaneously; thus, the midway point to the maximum extension was set as the ideal base position. Since the actuators' halfway point was 10mm, the number 10 was used in the equations.

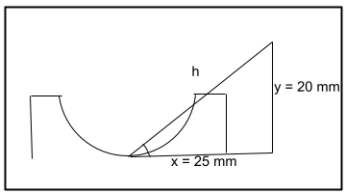


Fig. 9 Front view of the wrist's dominant left bionic arm actuator setup illustrating the key geometric parameters used in the wrist kinetic model: The actuators' maximum extension (y)mm and horizontal distance to the right actuators from the ball socket spherical centre (x)mm are illustrated while observed from the front of the wrist, and (h)mm is the hypotenuse distance from the ball socket spherical centre.

The set of equations for scenario one is listed below; the set of equations varies slightly depending on which scenario the hand would move.

$$\left.\begin{aligned} \mathrm{ex}_1 &= 10(y_f + y_{\mathrm{bend}}) \\ \mathrm{ex}_2 &= 10(y_f - y_{\mathrm{bend}}) \\ \mathrm{ex}_3 &= 10 + (y_f - y_{\mathrm{bend}}) \\ \mathrm{ex}_4 &= 10 + (y_f + y_{\mathrm{bend}}) \end{aligned}\right\} \tag{2}$$

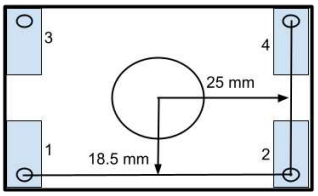


Fig. 10 Top view of the dominant left bionic arm wrist setup: Four linear actuators (blue) are positioned at the wrist's corner, housing a central ball-socket joint(circle). It shows the two-dimensional distance between the centre of the wrist and the actuator pairs.

In ex_1, ex is the actuator's extension, and the subscript number represents the actuator number. The terms y_f and y_{bend} represent the differences from the wrist's base position in flexion and bending motions. In Figure 9, y is the maximum extension of the actuators, and x is the distance to the actuators from the center of the ball socket joint. Before fixing the position of actuators inside the rectangle, certain conditions had to be met. For example, if the hand had to flex forward to the maximum position and then bend sideways in one of the directions, there is a high chance that one actuator would have input greater or less than the maximum and minimum positions that the actuators could take. In return, the actuators will not produce the intended movement, resulting in an inadequate representation. To address this issue, we have implemented a set of restrictions. The main problem was the total extension of the actuators, which is 20mm. It meant that if the combined actuation values from flex and bend exceeded the halfway point of the extension, i.e, 10mm, it would destabilize the hand. To avoid this, we computed a value that represented the proportion of the total value in both directions. If the sum of y_f and y_{bend} was greater than 10, the values were as follows:

$$\left.\begin{aligned} y_f &= \frac{y_{\text{flex}}}{y_{\text{Total}} \cdot 10} \\ y_{\text{bend}} &= \frac{y_{\text{bend}}}{y_{\text{Total}} \cdot 10} \end{aligned}\right\} \tag{3}$$

In equation 3 y_{Total} value is the maximum extension of the actuator. The above equation, which will be used only if the sum of y_f and y_{bend} exceeds 10; otherwise, the unchanged value inputs were used.

4.2 Design of Dominant Left Prosthetic

From rules 1 and 2, the dominant bionic arm should be assigned a higher dof and rigid-mechanism specifications to perform tasks involving precise grips and circular grasps. So we have assigned 11 DoF to the dominant left bionic arm and distributed them across the fingers, with a four-bar linkage mechanism and wrist, to meet the demands of the dominant role.

4.2.1 Structure of Fingers

The fingers consist of 2 different parts, proximal and distal. The primary difference between the human hand and the robotic arm was that the middle and distal phalanx of the human finger were combined into a single entity, such as the distal phalanx of the robotic finger. The fingers in the dominant left bionic arm were modified to mimic the movement of a human finger by adding a link attached to the arm's rear and the bottom front of the distal phalanx. This results in a so-called four-bar connectivity between the proximal and distal phalanxes as seen in Figure 11(d), which translates the naturally controlled movement of the fingers, necessary for precision and dexterity in performing tasks. The distance and lengths of each phalanx were calculated in advance to achieve the desired action/movement while actuating the finger.

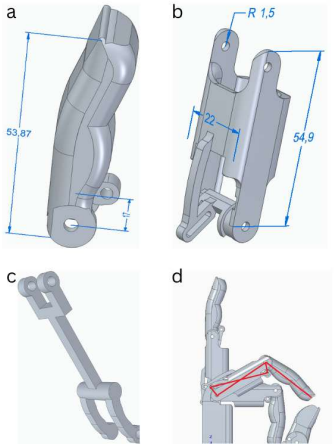


Fig. 11 Components of Finger: (a). Distal phalanx of the finger, (b). Proximal phalanx of the finger, (c). Bending rod used for four-bar linkage in each finger, (d). Visualization of a four-bar linkage in fingers(dimensions mentioned are in mm).

4.2.2 Structure of Thumb

The thumb has a distal and proximal phalanx; it also has metacarpal bones, just like fingers. The metacarpal bone of the thumb is surrounded by muscle, which makes it possible for the thumb to move in opposition. The thumb of the dominant bionic arm, see Figure 12, was also designed to achieve opposing motion against the fingers, in addition to flexion and extension, thereby facilitating a better grasp capability. The thumbs' articulation also incorporated a four-bar linkage, similar to the fingers; the bending rod was connected to the metacarpal and distal phalanx.

4.2.3 Structure of Palm

The palm design of the dominant left arm was more challenging because the motors had to be mounted within the palm to achieve controlled flexion and extension motion

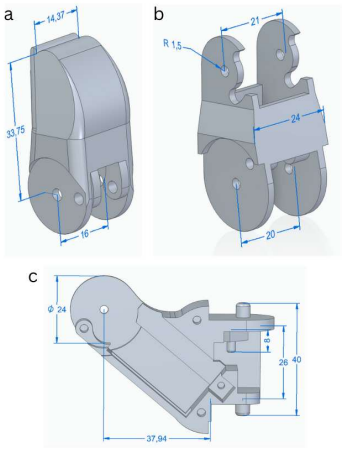


Fig. 12 Components of Thumb: (a). Distal phalanx of the thumb, (b). Proximal phalanx of the thumb, (c). Metacarpal of the thumb(dimensions mentioned are in mm).

of the finger, resulting in improved dexterity and improved force distribution for tasks requiring precision and strength. So, we intricately designed the palm to serve as a mounting platform for the linear actuators as seen in Figure 13, which added adduction and abduction to the thumb, resulting in higher degrees of freedom. The palm also had carefully positioned holes, and the dorsal-proximal holes serve as attachment points for the "bending link," which is connected to the distal phalanx, allowing the fingers to range or flex as desired. Wire channels were incorporated into the palm to enable the actuator to be routed toward the wrist and forearm; the CAD design of the palm is shown in Figure 13.

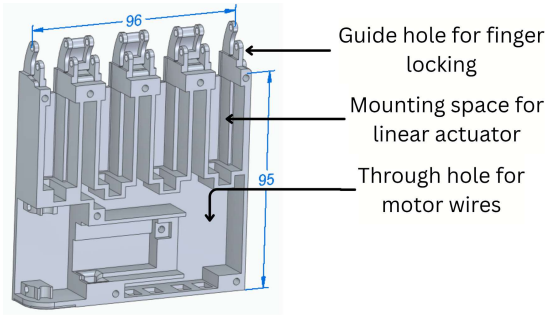


Fig. 13 Design details of Palm: Illustration of placements for linear actuators within it and guide holes for the finger-locking mechanism(dimensions mentioned are in mm).

4.2.4 Structure of Wrist

The wrist joint of the dominant left bionic arm is designed to strike a strong balance between precision tasks and a broad range of motion, closely mimicking the joint

kinematics of the human wrist. Two different actuation subsystems were assembled to achieve this critical wrist articulation. The first is the central ball socket joint, the biomechanical link between the palm and forearm sections. The second is the multi-actuator linear motor system.

4.2.5 Central ball and socket joint: The biomechanical link

The dominant left bionic arm wrist features a ball-and-socket joint as its core, which is 3D printed. We used PLA(Polylactic Acid), which has a very low friction coefficient, ensuring a smooth and efficient ball rotation over the socket. The ball-shaped joint allows wrist actuation in multiple planar directions, making it more suitable for dexterous manipulation. We assembled a ball bearing around the socket to add strength and fluidity to this joint. This combined actuation system efficiently reduces the mechanical loads on the actuators placed at the corners of the wrist, minimizing the torque and friction loss borne by the actuators.

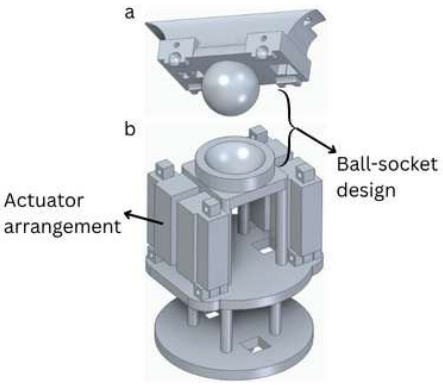


Fig. 14 Design details of Wrist: This design features an arrangement of four linear actuators within the wrist, integrated to a ball socket joint, engineered to facilitate radial, ulnar, flexion, and extension actuation.

4.2.6 Multi-actuator linear motor system

Four independent linear actuators actively drive the dexterous ball-and-socket joint. The placement of the linear actuators is precisely calculated and positioned around the ball-and-socket joint to provide synergistic control of the wrist movement. This multi-actuator system has the capabilities of performing combined and independent actuations of:

- **Flexion-Extension:** The combined actuation of linear actuators in the front and back of the ball socket joint motion through its sagittal plane, performs tasks that require precise control over gripping, reaching, and object manipulation.
- **Radial-Ulnar Deviation:** The combined actuation of linear actuators drives the wrist motion through the coronal plane, which is crucial for fine adjustments and tasks requiring lateral precision.

The coordinated movement of linear actuators combined with the mobility of the ball socket joint enables essential wrist articulation. The interaction between these two systems allows for dynamic wrist control with high positional accuracy of the linear actuators. Additionally, the rigidity of the wrist can be adjusted according to task requirements, making it smoother and more precise, while closely simulating the innate dexterity of the human wrist. The whole setup of ball socket joint with linear actuators is shown in Figure 14.

4.2.7 Structure of Forearm

The forearm of the dominant arm has a bi-part mechanism design that ensures optimal functionality and precise movements, as shown in Figure 15. It was designed with precision to accommodate four linear actuators, a rotational bearing, a small servo motor responsible for a wide range of wrist motion see figure 15, and a battery bank, enabling it to function for an extended period. The design consists of two significant corresponding parts that can be assembled with screws.

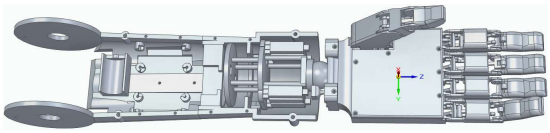


Fig. 15 The CAD design of the dominant left bionic arm: The figure showcases the full mechanical assembly, with the forearm section showing linear actuator arrangement.

4.3 Design of Non-dominant right prosthetic

From rules 1 and 2, the non-dominant bionic arm should be assigned a lower dof and compliant actuation specifications to perform tasks involving stabilisation that require individual control in fingers. So we have assigned 6 DoF to the non-dominant left bionic arm and distributed them across the fingers, using a tendon-compliance mechanism and wrist, to meet the demands of the non-dominant role.

4.3.1 Structure of fingers

The distal, middle, and proximal phalanx—the three interconnected portions of the prosthetic fingers on the non-dominant right bionic arm—form a miniature skeletal system similar to a human hand. "Artificial tendons" are employed in the actuation process; these tendons form a complete loop around the fingertip and pass through the palm and forearm, connecting to servos. Tendons are pulled by servo motor actuation, which creates rotating stresses in each finger joint to provide complete flexion as shown in Figure 16. Low-stretch braided fishing lines were used to reduce elongation under strain. Nonlinear rolling joints are incorporated into the arm design to replicate the structure of human finger joints, enabling efficient and natural mobility optimized for quick grasping, support, and stabilizing lifts. The distance and lengths of each phalanx were calculated in advance to achieve the desired action/movement while actuating the finger.

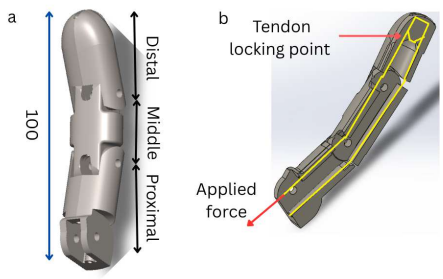


Fig. 16 Components of Index Finger:(a). Visualizing the arrangement of the finger with all three phalanges, (b). Illustration of an artificial tendon looping through the index finger(dimensions mentioned are in mm).

4.3.2 Structure of Thumb

The thumb of the non-dominant bionic arm is divided into three parts, namely the proximal, distal, and metacarpal, as shown in Figure 17. However, the opposability of the thumb was not achieved to the full extent due to the simplicity of its design. The thumb provides only one degree of freedom, flexion and extension, which are necessary for stabilization and support functions. Guide holes have been incorporated in the distal part to optimize orientation and prevent tendons from getting caught during actuation.

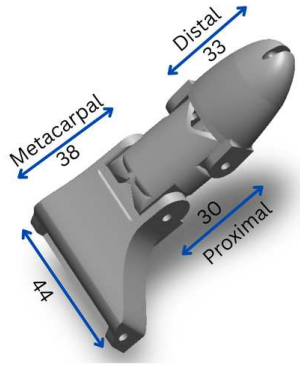


Fig. 17 Design of Thumb: The figure comprehensively illustrates the thumb design, highlighting its different design sections(dimensions mentioned are in mm).

4.3.3 Structure of Palm

The palm of the non-dominant right arm is very elementary, with no space to house the servo motors as depicted in the CAD design in Figure 18. The design features slots for each finger, where the proximal phalanx is secured to the palm with metal pins. The thumb opposition is easier to handle because the thumb is fastened to the palm with a propylene pin. An aperture on the palmar side of the palm allows the tendons to easily

pass through the forearm and attach to the horn of the servo motor. Furthermore, the base of the palm includes a component of the wrist rotation mechanism, connecting the palm and the upper forearm.

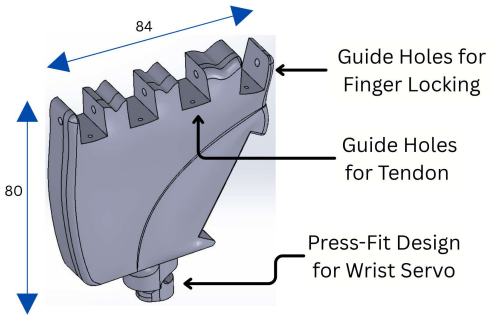


Fig. 18 Design details of Palm: The illustration details the palm design integrated with guide holes for tendon placement alongside additional guide holes for the finger locking mechanism and a press-fit design specifically designed for wrist activity(dimensions mentioned are in mm).

4.3.4 Structure of Wrist

The gear system for wrist rotation was challenging to design because standard servo motors have a ±90-degree maximum rotation range. To achieve specific arm positions, this would have required a mechanical block or less precise open-loop control methods. The easiest way to eliminate the gear system and angular position control was to directly fit the lower design of the palm to the servo shaft inside the upper forearm. Figure 19 shows the servo motor setup inside the upper forearm. This resulted in smooth actuation of wrist pronation and wrist supination, with reduced design complexity and cost, exhibiting the capability to support and stabilize, complementing the bi-manual task.

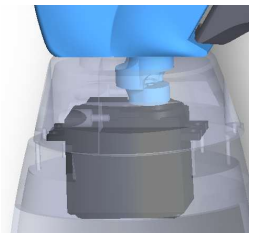


Fig. 19 Design of Wrist: The figure illustrates the implementation of press-fit design for seamlessly connecting the motor responsible for wrist actuation.

4.3.5 Structure of Forearm

The non-dominant arm's forearm is designed to accommodate six servo motors and a battery bank, facilitating easy assembly of tendons onto servo horns to function with

maximum efficiency and minimum friction see figure 20. Due to the integration of these components, the fingers and wrist can have smooth and controlled movements. The design initially was a single entity, but for printing and housing the easiness of tendons and motors, it was divided into separate components that could be assembled using screws.



Fig. 20 The CAD design of non-dominant right bionic arm: The figure showcases the full mechanical assembly, with the forearm section specifically illustrating the intermounting of motors.

5 Control Architecture for Bilateral Bionic Arm

5.1 Dominant left Prosthetic

The Actuonix PQ12 linear actuator was used in the dominant left bionic arm. This actuator was chosen because of its compact size, which allows it to fit comfortably in the palm. The stroke length of the linear actuator was 20 mm; using just half of its stroke length allowed for precise support of the four-bar linkage mechanism. An external microcontroller controlled the built-in position sensor feedback, which was internally controlled by a positive and negative reference potentiometer by implementing a Proportional-Integral-Derivative (PID) control regulator.[31] The dominant left bionic arm incorporated ten linear actuators and one servo motor in the forearm to facilitate wrist rotation. The servo motor used was the SG92R servo from Tower Pro, with an operating voltage of 5V and a stall torque of 2.5 kg/cm. [32] The dominant left bionic arm's microcontroller had an insufficient power output, so we used a TB6612FNG motor driver circuit to provide adequate power (1.2 A constant current per channel, up to 15V DC) for all actuators. [33]

5.2 PID-Regulator devised for Linear Actuator

We devised a PID regulator to smooth out the movements of the actuators. PID regulators combined with linear actuators proved to be effective in their operation, since the regulator could access both intended and present position, which is the cornerstone of the regulator. The devised PID regulator is shown in Figure 21 The values of intended position (IP) and present position (PP) are used to calculate error (e = IP - PP). The error is directly proportional to the distance between the intended and current positions of the actuators; i.e., the error is smaller when they are close to the intended position and larger when they are away from the intended position. This implies that if the output of the regulator were to represent the actuator's speed, the

actuator's speed would be slower as it approaches the intended position, resulting in smooth actuation.

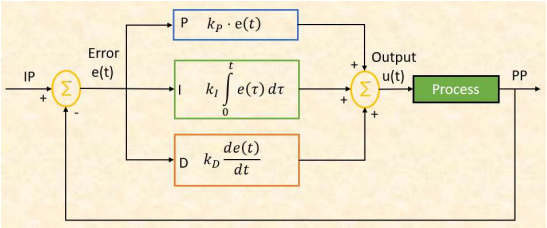


Fig. 21 PID regulator: The figure presents a block schematic of a PID regulator devised for a linear actuator incorporating feedback, where IP is the Intended Position and PP is the Present Position.

- The first part of the PID is the proportional part of the regulator. The proportional part includes the system error, along with its weighting parameter, denoted as K_p, as seen in equation (4), where the error $e(t) =$ Intended Position $-$ Present Position. If the error value is large, the output of the regulator is proportionately large, along with the weighing parameter K_p.
- The integral part takes into account the previous values and variables that were entered into the system.
- The final part of the regulator is the derivative part, which handles the future trend of the error. The regulator can predict the system's output based on the rate of change of the error. The higher the rate of change in error, the faster the system's response time. The derivative part is responsible for smoothening the curve, resulting in decreased overshoots.

The final combined equation with all three parts of the regulator with the output parameter u(t) is given as:

$$u(t) = \underbrace{K_P \cdot e(t)}_{\text{Proportional}} + \underbrace{K_I \int_0^t e(\tau)\,d\tau}_{\text{Integral}} + \underbrace{K_D \frac{de(t)}{dt}}_{\text{Derivative}} \tag{4}$$

5.3 Non-dominant Right Prosthetic

The non-dominant right bionic arm was housed with seven MG996R TowerPro servo motors.[34] These high-torque digital servo motors help pull the tendons smoothly without any stress on the hand during flexion and extension. Two 32-bit Arduino Due microcontrollers controlled the arms.[35]

5.4 Signal Initiation

Two different control systems have been modified for the bionic arm extremities. The dominant left bionic arm utilizes a pressure sensor module to regulate complex movements precisely. On the other hand, the non-dominant right bionic arm is controlled naturally and intuitively with the help of a resistive glove that translates finger

movements into comparable bionic arm actuation. By utilizing this distinctive control mechanism, we can evaluate the individual efficiency of two bionic arms as shown in Figure 22 and discover their benefits and drawbacks. The control systems used here are for mechanical bench-top validation; they are not a proposed clinical validation solution.

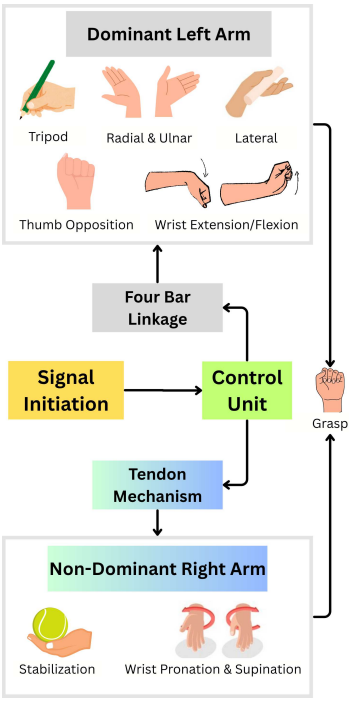


Fig. 22 Signal initiation: The control system utilizes a resistive glove for the non-dominant bionic arm and a customized controller for the dominant bionic arm as inputs to demonstrate the distinctive functional prehensile grip and grasp patterns in both bionic arms. The grasp pattern is seen in both bionic arms, so it's placed in between.

5.5 Device fabrication

The program used to create the 3D models of the bionic arm's parts is called Solid-Works. The Solid Works program focuses on assembly rather than single-part designs. The **Snapmaker A350** was used to print the design model of the bionic arms. The CAD files were converted to STL files and sliced using Snapmaker Luban cite Snapmaker2023.

Polylactic acid (PLA) was selected for 3D-printed prosthetic components due to its favourable mechanical properties (strength, stiffness, and lightweight) that support functionality, wearability, and ease of processing and customisation using fused deposition modelling techniques, and also PLA has low friction, which helped for smooth movement of the ball-and-socket joint in the dominant left bionic arm [36].

6 Discussion & Conclusion

The results from the bench-top validation confirm that the functional differences incorporated into the bilateral solution translate into distinct mechanical performance, with each arm fulfilling its assigned role as specified by the proposed framework. The dominant arm performed various grip configurations, namely key grip, lateral pinch, circular grasp and thumb opposability. As shown in Table 2, the dominant arm achieved a lifting capacity of approximately 150g per finger across all repeated trials, demonstrating consistent trajectory motion enabled by a four-bar linkage mechanism. The wrist of the dominant arm also demonstrated coordinated multiple degrees of freedom as expected by the framework's dominant requirements. The results align with the framework's prediction rules 1 and 3 as mentioned in Table 2, which state that a system with high DoF using rigid, deterministic actuation will produce repeatable, high-accuracy, high-precision manipulation. The non-dominant arm with a tendon-compliance mechanism achieved dynamic grasp conformity to the shape of the objects, and the total assembly could lift objects up to 600 g and rotate the wrist 180 degrees to orient the objects during stabilisation tasks. These results also align with the framework's prediction rules 2 and 4 as mentioned in Table 2.

The wrist of the dominant arm demonstrates coordinated multiple degrees of freedom in accordance with the framework requirements for the dominant arm. While trying to hold the bottle, the grasp grip is activated simultaneously with radial deviation, ulnar deviation, and wrist flexion as depicted in Figure 4(b–d), which helps the hand grasp the bottle and return to its steady position quickly. This is achieved by actuating the linear actuators in pairs: two extend, and the other two retract, accomplishing the task efficiently without loss of positional accuracy. This simultaneous multi-axis actuation is exactly the behaviour needed to support the dominant arm's predictive feedforward mechanism. Apart from this, the dominant left bionic arm also performed other grasps that are also expected by the framework: circular grasp, precision, pinch, and thumb-opposing capabilities, as shown in Figure 3. Consistent trajectory motion observed during the repeated trials suggests that the four-bar linkage mechanism along with a multi-axis wrist configuration has the capability to produce the required repeated trajectory motion for fine motor skills using linear actuators, incorporated with position feedback and a PID regulator for the smooth actuation control. At the same time, the non-dominant right bionic arm with the tendon compliance mechanism demonstrated load-adaptive behaviour and stabilisation in accordance with the frameworks of the non-dominant hemisphere. One primary and predominant degree of freedom includes pronation and supination. In the experimental demonstration from Figure 7, we investigated how dynamic mass influences effective lift by utilising the pronation of the non-dominant right bionic arm. In particular, a bottle partially filled with liquid is placed horizontally, and the non-dominant bionic arm, which can rotate 180 degrees, is used to turn it upright before lifting it. With this technique of lifting the bottle, the torque required for lifting will be considerably lower than that required for direct horizontal lifting because the centre of mass (COM) is moved nearer to the grasping position, aligned with gravity, making the wrist to easily rotate and pour water instead of fighting against the gravity, ensuring a stable lift and mimicking the

natural, energy efficient strategy as human. During the whole process of demonstration, the hand had to vary its conformity based on the shifting centre of mass of the bottle, which was made possible through the tendon compliance in the fingers, demonstrating the impedance control mechanism that Rule 2 specifies for the non-dominant arm, which states that joint stiffness varies for external load disturbances rather than following a fixed trajectory. These observed results suggest that non-dominant arms with simplified mechanical structure achieve their intended functional roles, i.e., stabilisation and adaptive grasp, according to the framework.

Existing commercial bionic arm prosthetic solutions, including the i-limb, Open Bionic Hero Arm, Bebionic, and Hannes Hand, offer high dexterity, greater degrees of freedom and aesthetics, enabling users to perform daily living activities with maximum capability. Still, they are primarily designed for unilateral users. So, irrespective of which hand the user has lost or whether the user is a bilateral amputee, they treat both arms as functionally identical. This approach, when applied to bilateral amputees with the same degrees of freedom, mechanical design complexity, and functional roles, conflicts with the amputee's well-established, fundamentally asymmetric neuromotor system. This design symmetry in the existing prosthetics solution could potentially be the reason for the elevated cognitive load and mental fatigue as reported in bilateral users, in which the user has to adapt to the dominant-role precision tasks with a device which has the same functional profiles and the same design complexity on both limbs, without considering their innate asymmetric behaviour. With our experience in biorobotics [37, 38], we observed a significant engineering gap that motivated the present work, in which handedness is formalised as the primary design parameter. It is also evident from the available prosthetics research publications that the design space for bilateral bionic arms, with hand dominance as a primary design factor, has received very little systematic attention. Most of the research addresses unilateral amputees, and the bilateral system would adopt the unilateral design for both arms rather than purpose-built bionic solutions. A side-by-side comparison of the commercially available prosthetic solution and the proposed bilateral framework solution is provided in Table 2, showing that the asymmetrically incorporated prosthetic solution with lower DoF produces a different performance profile from existing solutions that treat both arms as identical. Prosthetic abandonment among the upper limb users is a persistent and significant clinical problem.

Approximately 44% of upper limb amputees are affected globally; additionally, patients who lost their dominant hand demonstrated high abandonment (55.5%) compared to non-dominant hand amputees (14.3%), and prosthetic acceptance rates vary greatly by amputation side (dominant/non-dominant). It shows that 86 per cent of non-dominant amputees accepted their prosthesis, when compared to only 45 per cent of dominant hand amputees.[39, 40] There is a higher abandonment rate in dominant arm amputees because they lose their dominant limb, whose hemisphere is responsible for tasks involving high precision and complex trajectories; no existing bilateral system addresses this issue to restore the dominant functional specialisation. After the loss of the dominant arm, amputees tend to consider the other arm to take this role instead of prosthetics, which is very difficult in practice because the non-dominant arm hemisphere has to control demands for which it is not optimised. The possible

effectiveness of bilateral prosthetic design solutions in reducing abandonment rates, shortening rehabilitation, or lowering perceived cognitive demand requires clinical evaluation with bilateral amputee participants as the next step. The current work establishes foundational knowledge on which future implementation can be built. Arm dominance could play a crucial role in rehabilitation; dynamic dominance literature suggests that the dominant arm has stronger cortical motor memory, which the dominant hemisphere sustains through years of preferential use of the dominant limb for daily activities. These remain as phantom motor intent in the dominant hand even after amputation.[10, 29] Therefore, a prosthetic dominant-arm design that matches the functional profile of the dominant brain hemisphere, according to the proposed framework, is expected to integrate with more ease with the user's motor lateralisation than a symmetrical device would.

The advanced additive manufacturing approach for this proof of concept supports the broader customisable principle the framework enables. With the PLA fabrication technique, it is possible to scale the design with utmost efficiency without retooling, enabling patient-specific adaptation to individual anthropometrics. The scalability is consistent with the generalised framework design principle. In principle, it can also produce an equivalent prosthetic configuration for a right-hand-dominant amputee.

This work presents a preliminary conceptual and task-informed engineering framework for bilateral prosthetic design, grounded in how humans naturally divide tasks between dominant and non-dominant arms. This complementary design approach may enhance the natural division of labour seen in humans. The results from bench-top evaluations confirm that the asymmetric bilateral system prototype derived from the framework produces mechanically viable, role-differentiated prototypes, each fulfilling its assigned functional role. This bilateral solution is presented as a proof of concept rather than a user-centred investigation; this work provides a foundational step towards the possibility of reducing the cognitive burden and enabling more intuitive bilateral prosthetic use. The scope of this paper is limited to addressing the fundamentally unexplored engineering gap: the absence of hand dominance and asymmetric design principles in bilateral prosthesis systems.

While prosthetic compliance plays an important role, this proposed design framework does not preclude compliance integration; rather, it provides the foundation on which compliant elements can be incorporated in future design iterations before clinical deployment. The control interfaces for the bilateral system, namely the pressure sensor and resistive glove, were used solely for mechanical bench-top validation and were not proposed as a clinical-grade solution. In subsequent iterations, the improvised bilateral system's control interfaces will be replaced with advanced proprioceptive feedback systems enabled by neural feedback pathways. Following successful mechanical, compliance, and control-interface iterations of this pre-clinical phase prototype, clinical validation involving bilateral amputees will be conducted to assess these outcomes.

Supplementary information. Video S1: Demonstration of the dominant left bionic arm performing precision grip tasks, showing individual finger articulation through the four-bar linkage mechanism and wrist rotation with radial/ulnar deviation.

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Declarations

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- **Additional information:** On behalf of all co-authors, I declare that we have no financial, personal, or professional competing interests that could inappropriately influence or bias the content or findings presented in this manuscript. All authors have read and approved the final manuscript. We confirm that this work is original, has not been published previously, and is not currently under consideration elsewhere.
- **Data availability:** Data will be made available on request.
- **Author contribution: Arvind Selvan Chezhian:** Writing – original draft, Writing – review & editing, Methodology, Visualization. **Bobins Augustine:** Conceptualization, Supervision, Investigation. **Emil Bennedicks:** Methodology, Visualization. **Silvestro Micera:** Supervision **Robin Augustine:** Methodology, Investigation, Conceptualization, Funding acquisition, Project administration, Supervision.

References

[1] Ziegler-Graham, K., MacKenzie, E. J., Ephraim, P. L., Travison, T. G. & Brookmeyer, R. Estimating the prevalence of limb loss in the united states: 2005 to 2050. *Archives of Physical Medicine and Rehabilitation* **89**, 422–429 (2008). PMID: 18295618.

[2] Pasquina, P. F., Miller, M. & Carvalho. Special considerations for multiple limb amputation. *Current Physical Medicine and Rehabilitation Reports* **2**, 273–289 (2014). PMID: 25411651.

[3] Castellini, C. in *Upper limb active prosthetic systems—overview* (eds Rosen, J. & Ferguson, P. W.) *Wearable Robotics: Systems and Applications* 365–376 (Academic Press, 2019).

[4] Vasdeki, D., Barmpitsioti, A., De Leo, A. & Dailiana, Z. How to prevent hand injuries—review of epidemiological data is the first step in health care management. *Injury* **55**, 111327 (2024).

[5] Roşca, A. C., Baciu, C. C., Burtăverde, V. & Mateizer, A. Psychological consequences in patients with amputation of a limb. an interpretative-phenomenological analysis. *Frontiers in Psychology* **12**, 537493 (2021).

[6] Jing, S. S. Hand dominance: nature, nurture, and relevance for hand surgeons. *Journal of Hand and Microsurgery* **14**, 111–112 (2022).

[7] Peterson, J. M. & Lansky, L. M. Left-handedness among architects: Partial replication and some new data. *Perceptual and Motor Skills* **45**, 1216–1218 (1977). PMID: 604901.

[8] Kousaka, H., Mizoguchi, H., Yoshikawa, M., Tanaka, H. & Matsumoto, Y. *Role analysis of dominant and non-dominant hand in daily life*, 3972–3977 (IEEE, 2013).

[9] Isabel, C. & Adams, J. A comparison of dominant and non-dominant hand function in both right- and left-handed individuals using the southampton hand assessment procedure (shap). *The British Journal of Hand Therapy* **8**, 4–10 (2003).

[10] Sainburg, R. L. Evidence for a dynamic-dominance hypothesis of handedness. *Experimental Brain Research* **142**, 241–258 (2002).

[11] Bagesteiro, L. B. & Sainburg, R. L. Nondominant arm advantages in load compensation during rapid elbow joint movements. *Journal of Neurophysiology* **90**, 1503–1513 (2003).

[12] De Kovel, C. G., Carrión-Castillo, A. & Francks, C. A large-scale population study of early life factors influencing left-handedness. *Scientific Reports* **9**, 584 (2019).

[13] Sartarelli, M. Handedness, earnings, ability and personality. evidence from the lab. *PLoS ONE* **11**, e0164412 (2016).

[14] Coren, S. Left-handedness and accident-related injury risk. *American Journal of Public Health* **79**, 1040–1041 (1989).

[15] Flatt, A. E. Is being left-handed a handicap? the short and useless answer is "yes and no". *Proceedings of Baylor University Medical Center* **21**, 304–307 (2008). PMID: 18628930.

[16] Atherton, R. & Robertson, N. Psychological adjustment to lower limb amputation amongst prosthesis users. *Disability and Rehabilitation* **28**, 1201–1209 (2006). PMID: 17005481.

[17] Taras, J. S., Behrman, M. J. & Degnan, G. G. Left-hand dominance and hand trauma. *The Journal of Hand Surgery* **20**, 1043–1046 (1995).

[18] Dexheimer, B. & Sainburg, R. L. When the non-dominant arm dominates: the effects of visual information and task experience on speed-accuracy advantages. *Experimental Brain Research* **239**, 1097–1108 (2021).

[19] Atzori, M. & Müller, H. Control capabilities of myoelectric robotic prostheses by hand amputees: a scientific research and market overview. *Frontiers in Systems Neuroscience* **9**, 162 (2015).

[20] Mendez, V., Iberite, F., Shokur, S. & Micera, S. Current solutions and future trends for robotic prosthetic hands. *Annual Review of Control, Robotics, and Autonomous Systems* **4**, 595–627 (2021).

[21] Micera, S. & Shokur, S. Our research path toward the restoration of natural sensations in hand prostheses. *Artificial Organs* **48**, 937–942 (2024).

[22] Ottobock. SensorHand Speed – Product Overview (8E38=8). https://www.ottobock.com/en-sc/product/8E38--8-61019 (2026). Accessed: 30 October 2026.

[23] Scheme, E. & Englehart, K. Electromyogram pattern recognition for control of powered upper-limb prostheses: State of the art and challenges for clinical use. *Journal of Rehabilitation Research and Development* **48**, 643–659 (2011). PMID: 21938652.

[24] Earley, E. J., Piazza, C. & Turner, K. L. *A taxonomy for commercially available myoelectric terminal devices* (2024).

[25] IIT Rehab Technologies Lab. Hannes: A prosthetic hand developed at iit. https://rehab.iit.it/hannes (2023). Accessed: 30 October 2026.

[26] Open Bionics. Hero arm overview. https://openbionics.com/en/hero-arm-overview/ (2023). Accessed: 30 October 2026.

[27] Ottobock. 8e70-61081 myobock system — product overview. https://www.ottobock.com/en-us/product/8E70-61081 (2023). Accessed: 30 October 2026.

[28] Bagesteiro, L. B. & Sainburg, R. L. Handedness: dominant arm advantages in control of limb dynamics. *Journal of Neurophysiology* **88**, 2408–2421 (2002).

[29] Sainburg, R. L. & Kalakanis, D. Differences in control of limb dynamics during dominant and nondominant arm reaching. *Journal of Neurophysiology* **83**, 2661–2675 (2000).

[30] Duff, S. V. & Sainburg, R. L. Lateralization of motor adaptation reveals independence in control of trajectory and steady-state position. *Experimental Brain Research* **179**, 551–561 (2007).

[31] Actuonix Motion Devices. Pq12-63-6-s linear actuator – product page. https://www.actuonix.com/pq12-63-6-s (2023). Accessed: 30 October 2026.

[32] ProtoSupplies. Servo motor micro sg92r – product page. https://protosupplies.com/product/servo-motor-micro-sg92r/ (2025). Accessed: 30 October 2026.

[33] SparkFun Electronics. Motor driver – dual tb6612fng (with headers) – product page. https://www.sparkfun.com/products/14450 (2025). Accessed: 30 October 2026.

[34] TowerPro. Mg996r servo motor – product page. https://towerpro.com.tw/product/mg996r/ (2023). Accessed: 30 October 2026.

[35] Arduino. Arduino due – official store product page. https://store.arduino.cc/products/arduino-due (2023). Accessed: 30 October 2026.

[36] Kehinde Aworinde, A., Oluropo Adeosun, S., Adekunle Oyawale, F., Titilayo Akinlabi, E. & Akinlabi, S. A. *Parametric effects of fused deposition modelling on the mechanical properties of polylactide composites: a review*, Vol. 1378, 022060 (IOP Publishing, 2019).

[37] Augustine, B., Chezhian, A. S., Perchiazzi, G., Voigt, T. & Augustine, R. Scale adaptive robotics: Soft robot for multi-scale applications. *Engineering Archive (engrXiv)* (2025). Preprint.

[38] Chezhian, A. S., Trollsås, E., Augustine, B. & Augustine, R. Maufroy, C. & Schneider, U. (eds) *Wireless control of 3d-printed prosthetic hand using fat-intrabody communication.* (eds Maufroy, C. & Schneider, U.) *Proceedings of the 4th WearRAcon Europe Conference 2025*, 30–31 (Fraunhofer IPA, Düsseldorf, Germany, 2025).

[39] Østlie, K. *et al.* Prosthesis rejection in acquired major upper-limb amputees: a population-based survey. *Disability and Rehabilitation: Assistive Technology* **7**, 294–303 (2012).

[40] Salminger, S. *et al.* Current rates of prosthetic usage in upper-limb amputees—have innovations had an impact on device acceptance? *Disability and Rehabilitation* **44**, 3708–3713 (2022).

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