The Neural Resource Allocation Problem when enhancing human bodies with extra robotic limbs

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Abstract

The emergence of robotic body augmentation provides exciting innovations that will revolutionize the fields of robotics, human-machine interaction and wearable electronics. While augmentative devices like extra robotic arms and fingers are informed by restorative technologies in many ways, they also introduce unique challenges for bidirectional human-machine collaboration. Can humans adapt and learn to operate a new robotic limb collaboratively with their biological limbs, without restricting other physical abilities? To successfully achieve robotic body augmentation, we need to ensure that by giving a user an additional (artificial) limb, we are not trading off the functionalities of an existing (biological) one. In this manuscript, we introduce the "*Neural Resource Allocation Problem*" and discuss how to allow the effective voluntary control of augmentative devices without compromising the control of the biological body. In reviewing the relevant literature on extra robotic fingers and arms, we critically assess the range of potential solutions available for the *Neural Resource Allocation Problem*. For this purpose, we combine multiple perspectives from engineering and neuroscience with considerations from human-machine interaction, sensory-motor integration, ethics, and law. Altogether we aim to define common foundations and operating principles for the successful implementation of robotic body augmentation.

Introducing robotic body augmentation and the neural resource allocation problem

With robotic body augmentation — the augmentation of humans' physical abilities via robotic systems[1] — we are witnessing the rise of a new class of technologies, which are designed to resemble human limbs in their functionality while being integrated with the users' natural abilities. Traditionally, such devices have been developed to substitute a missing or impaired body function (i.e., restorative technologies), most famously bionic legs and arms for substitution of missing limbs[2,3] or exoskeletons for restoring impaired movement[4]. But from a system design perspective, the same technological foundation that allows a functionality which approximately matches that of a body part to be implemented, can also be exploited for augmenting the sensory and motor capabilities of an able-bodied individual. As such, human body augmentation is no longer science fiction. From the engineering side, a whole spectrum of human body enhancement now exists, ranging from technologies for restoration or compensation of functions in patients with physical limitations (Fig. 1A-

B) to augmentation beyond (healthy or disabled) subjects' physical abilities (Fig. 1C-D).

The examples in Fig. 2A show use cases of sensorimotor augmentation that are achievable with existing extra robotic limbs (XRLs)[5–9], such as extra robotic arms that enable holding and manipulating objects simultaneously or extra robotic fingers that stabilize a grip while opening a jar with only one hand. But more complex applications are likely to emerge in the future (Fig. 2B). For example, a doctor using an XRL could perform a surgical procedure without the need for an assistant; a watchmaker could use an XRL to perform a complex manipulation task, as screwing a component while holding a watch with his natural hands. Recent achievements in bidirectional human-machine interfaces pave the way for a future of augmented bodies, introducing the possibility that restorative and augmentative technology might eventually become two sides of the same coin[10].

Extra robotic arms (XRAs) and extra robotic fingers (XRFs) share attributes with existing robotics paradigms — such as prosthetics, wearable robotics, teleoperation, and human-robot collaboration —yet possess unique features and functionalities. We formalize the distinctive aspects of the XRAs/XRFs in figure 3A; conceptually, they sit in an unexplored region of a three-dimensional space defined by the control strategy with respect to the biological limbs, the level of enhancement provided by the device, and the device wearability. Following this formalization, they are defined as a *wearable* technology that can be controlled *independently* and/or *simultaneously* with the biological limbs. This warrants augmentation a new field with its own scientific and technological foundations and challenges.

Compared the other established robotic paradigms, XRAs/XRFs enhance (i.e., add to) a users' physical abilities (Fig. 3B, i-iv), rather than substituting a lost function (e.g., Fig. 3B (v) exoskeletons or (vi) prosthetics), or rerouting an existing function[11] (e.g., Fig. 3B (vii) robotic arms used in teleoperation). Moreover, they do not rely on an autonomous agent that interprets human intentions (e.g., Fig. 3B (viii) collaborative robotics) but instead are controlled at the user's own will. As such, while augmentation and substitution technologies face some similar technical challenges (e.g., developing light-weight wearable systems or increasing battery duration), robotic augmentation introduces new conceptual and practical challenges, which we will explore below.

As an extension of the user's sensorimotor system, XRAs and XRFs are meant to be simultaneously controlled with the biological arms and fingers in an effective and intuitive way. This integration with the human body poses the urgent question of whether and how the human brain can support the control of extra-limbs. People born with six digits, for example, have dedicated nerves, muscles, and dedicated representations in the brain's sensorimotor cortex to control the extra finger and achieve good motor performance[12]. Humans wearing extra robotic limbs cannot count on such a dedicated "neural hardware," so they need to adjust their "software" (i.e., neural activities) to efficiently control the extra robotic limb. Existing solutions involve 'highjacking' the neural resources originally devoted to our own body. This concept leverages on the notion of soft embodiment[11], which involves recycling neural and cognitive resources for the effective control of new functions. But for augmentation, much unlike substitution, we cannot harness "freed up" resources, such as the residual nerves in the arm of an amputee used for controlling a prosthesis. Moreover, unlike non-wearable teleoperation, augmentation should not interfere with the motor control of a user's biological limbs. Therefore, the challenge lies in operating the robotic limb without incurring costs to the rest of the body. We refer to this unique challenge, which distinguishes augmentation technology from most other assistive and restorative technologies, as the *Neural Resource Allocation Problem.* Put simply, this denotes the channeling of motor commands and sensory information to and from the augmentative device without hindering the motor control of biological limbs.

In the following, we wish to critically assess the range of potential solutions available to address the *Neural Resource Allocation Problem* when designing bidirectional control strategies for a new body part, from both a neuroscience and engineering perspective. We will review the first technologies pioneering the field, specifically focusing on XRFs and XRAs. While these technologies provide a first proof-of-concept for the feasibility of upper limb motor augmentation, they also highlight the many technical and conceptual challenges that are still unresolved. As such, we will consider how to best allow the effective and effortless voluntary control of these devices without compromising the voluntary control of the biological limbs. We will describe current limitation of the existing technologies used to capture motor intension and the key enabling principles that will help the field move forward. Further, we will address the problem of providing somatosensory information about the state of these devices without interfering with thesensory inputs coming from the biological limbs. Finally, we will highlight some of the societal, ethical, and legal aspects of extra limbs, which cannot be excluded from a discussion on the future of this emerging technology.Together, we aim to address the *Neural Resource Allocation Problem* and define common foundations and operating principles for the successful implementation of motor augmentation.

Motor control of extra robotic arms and fingers

As highlighted above, the operation of XRFs and XRAs requires the coordinated motor control of a robotic limb without the physiological infrastructure to guide these movements. Therefore, to operate the device, motor resources devoted to another (biological) body part need to be employed. Hereby, the key challenge is to provide a reliable readout of motor signals, while minimally disrupting the functionality of the biological body part. Several approaches have been proposed, exploiting – among others – muscle or brain interfaces to achieve coordination with the biological limbs[6,13]. In light of this, an important concept we want to introduce here is the "**motor task null space**" (Fig. 4). To define the null space, we need to refer to a task involving the biological limbs. Because of musculoskeletal and neural redundancy[14], different but equivalent body motions, muscle activation patterns, and neural activity patterns can be used to perform the task. The motor task null space then geometrically describes the set of all motor control variations — at the kinematic, muscular, or neural level — that do not impact the biological limbs' performance on that task.(Fig. 4). In other words, the successful simultaneous control of extra limbs requires the effective exploitation of motor control variations whose effect is negligible on the control of the biological limbs involved in the task. The motor task null space is thus at the very foundation of the enhancement. It is captured by the sensing part of the human- XRF/XRA interface and transformed into motor control commands for the device. The nature of the signal captured determines the type of motor task null space: (i) kinematic, (ii) muscular, and (iii) neural. We report in Table 1 relevant examples from the literature of control strategies based on different levels of the motor task null space and their outcomes. The "**kinematic null space**" refers to a subset of vectors whose components are samples of kinematic variables (e.g., joint angles) that characterize the movements of the biological limbs and are captured by motion capture systems, akin to those based on wearable technology[15,16]. As illustrated in Fig. 4, we can subdivide the null space into two orthogonal subspaces according to the kinematic variables involved. The "task-extrinsic null space" spans null space directions representing motions of all biological body parts not directly involved in the motor task. For instance, when force sensors are placed underneath a user's big toes to control two degrees of freedom, flexion/extension and adduction/abduction, of a robotic finger, mounted on a healthy subject's hand (example (i) in Fig. 3B, Table 1)[7]. In contrast, the "task-intrinsic null space" spans null space directions representing motions that are restricted to the limbs directly involved in the task. For example, a push-button was used to control an XRF attached to the wrist of the same hand used to press the button[17] (example (iv) in Fig. 3B, Table 1). It is worth noting that even though the task-extrinsic null space might intuitively seem like a better choice because it does not inherently interfere with the task, it is not always a practical solution for real-world tasks that require all limbs (e.g., engaging in bimanual manipulation while walking). From a neuroscience perspective, the task- intrinsic null space might then offer sensorimotor and cognitive resources that are more relevant for the task. For example, there are clear advantages to using hand muscles to control the XRF/XRA. Some of them relate to the existing neural infrastructure for supporting hand function – the connectome of the motor system makes motor control of the arm and hand specifically suited for this. Other advantages relate to the notion of motor synergies[18] – if we could take advantage of already existing motor synergies this might ease learning and control of the XRF/XRA.

The "**muscular null space**" refers to the subset of muscle activation vectors that do not generate task space forces. The elements of a muscle activation vector are samples of the variables that express the level of activation of a set of muscles (or motor units), as estimated from electromyography (EMG) signals captured by wearable electrodes. Any muscle activation vector can then be decomposed into two orthogonal components: a force generating component and a null space component. Thus, a muscular null space can be controlled independently from force. For instance, the co-contraction of a pair of antagonist muscles corresponds to a muscular null space vector that can be modulated during force generation or by itself. While the muscular null space may overlap with the kinematic null space, there are more muscles than joints, so the dimensionality of the muscular null space is generally larger than that of the kinematic null space. As such, the muscular null space offers additional opportunities to interface with the motor system without requiring explicit movements. For example, the volitional modulation of the motor neurons beta-band activity[19], to some extent independently from muscle contraction, belongs to the muscular null space. An advantage of the task-extrinsic muscular null space for an upper limb task is that it can elicit contraction of muscles with no action on the upper limb joints. This may involve using abdomen or forehead muscles for instance – both of which have previously been exploited for the control of XRAs and XRFs respectively (see example (ii) on Fig. 3B, Table 1)[6,9,20,21]. Meanwhile, the task-intrinsic muscular null space would involve the co-contraction of pairs of antagonist muscles (e.g., biceps and triceps) of the arm involved in the task. This could be exploited to control extra robotic limbs without interfering directly with the user's manipulation capabilities. However, while co-contraction can be modulated voluntarily[22], it is used naturally to regulate the mechanical impedance of the arm rather than to control extra robotic limbs. Thus, task-intrinsic muscular null space control constitutes a new motor skill that requires learning and practice. It remains to be understood how fast users can learn such motor skills[23], whether fatigue could be an issue with this approach, and what performance can be achieved (e.g., how many extra degrees of freedom can be controlled simultaneously with the biological limb and how accurate is the resulting motor control[24]).

Finally, the **"neural null space"** (Fig. 4) refers to a subset of vectors whose components are neural activity signals that can be independently modulated while performing the motor task. These can be neural activity signals from individual cortical neurons recorded by implanted electrodes or cortical neural ensembles recorded by EEG electrodes. The neural null space is best illustrated by the implementation of brain-machine interfaces (BMIs)[25–27]. Indeed, foundational work shows that both non-human and human primates can learn to control the firing rate of neuronal ensembles or even single neurons in the motor cortex in order to operate a robotic or virtual limb without impairing the control of biological limbs[28–31] BMIs with individual neuron recordings may seem like an ideal candidate for motor augmentation, making it possible to harness dedicated neural patterns for the motor control of extra robotic limbs. However, brain recordings conducted via cortically implanted electrodes are, to date, an unsuitable technique for healthy users, given the severe safety issues that could arise (e.g., surgery-related risks or post-surgery infections). Conversely, the extraction of relevant information by non-invasive BMIs (typically using EEG signals[25]) (see example (iii) on Fig. 3B, Table 1) is, in practice, challenging when aimed at controlling XRAs/XRFs. This is because the brain signals of interest would be inevitably mixed with those arising from other cortical activation patterns, including those related to the control of the biological limbs. In unconstrained environments, EEG recordings are also prone to signal contamination due to physiological and non-physiological artefacts (e.g., head or limb motion and power-line interference)[32]. In other words, it is difficult to orthogonalize the task null space.

We report in Table 2 the existing sensing technologies used for all three types of motor task null space and their current limitation. We identify the key missing principles, which future researchers should tackle to allow further development of XRLs. For example, while kinematic and muscular task null spaces – either intrinsic or extrinsic – can already be applied effectively to control extra limbs, they currently only permit control of a limited number of degrees of freedom. Meanwhile, the development of interfaces based on the muscular null space is limited by the recording stability and muscle fatigue. The neural null space requires safer approaches for recording single neurons, minimally invasive EEG probes, better filtering technologies, and more robust portable EEG systems. In general, the learning curve for mastering the null spaces is unknown.

Hybrid solutions inspired by collaborative robotics could address some of the intrinsic limitations of human-machine interfaces, such as the limited degrees of freedom. This could be done, for example, by employing intelligent sensorized robotic devices to exploit the shared control paradigm for the low-level kinematic calculations[33], which can extend dexterity in XRAs and XRFs and smooth the learning curve.

Sensory feedback for extra robotic arms and fingers

Numerous studies have demonstrated the importance of somatosensory feedback for dexterous and intuitive motor control in healthy subjects[34] and in amputee patients for efficiently controlling a prosthetic device[3,35–37]. Yet, due to the *Neural Resource Allocation Problem* facing augmentation technology, there are currently only few examples of sensory feedback for XRFs and XRAs (see Table 1). That is, akin to motor control, it is a unique challenge to deliver sensory information about extra robotic limbs without incurring costs to the sensory resources allocated to other body parts. This requires exploiting what we define here as "**sensory complementary space**" (Fig. 4), which consists of all the sensory information that can be provided without interfering with the sensory flow coming from the biological limbs. The sensory feedback can be presented to the limbs involved in the task ("task-intrinsic sensory complementary space") or to another body part ("task-extrinsic sensory complementary space"). The need to identify a null space poses a unique challenge to augmentation that is not faced by other levels of enhancement such as restoration. But the literature on sensorized prostheses for amputees[35], as well as non-invasive approaches inspired by sensory substitution and sensory remapping displays[35], can inspire potential solutions for implementing sensory feedback in extra robotic limbs. For instance, sensory feedback displays for XRAs and XRFs would rely on the user's natural sensory pathways to convey information from artificial receptors to cope with a sensory deficiency – that of the extra robotic limbs – without interfering with other perceptual processes.

Given the wearable nature of extra robotic limbs, it is important to note that a somatosensory input is inherently present at the interface between the device and the user's body, providing implicit sensory feedback. In a series of studies, motor control was found to be improved when physically wearing an XRA, operated via the task-extrinsic muscular null space, compared to controlling a simulated XRA[9,38]. This indicates that there might already be some valuable sensory feedback inherent to wearing an extra robotic limb that supports its motor control. In the design and development of future XRLs this can be usefully taken into account, by considering more rigid interfaces rather than compliant ones and selecting sensitive locations for the body anchoring. Moreover, there is recent evidence[39] that the motor system takes advantage of somatosensory information from the controller of an XRF. In task-intrinsic implementations the physical proximity might aid this process even further. Alternatively, sensory information cues that typically act at different time scales (e.g., event-driven feedback[36], meaning stimulation at discrete events as opposed to continuous stimulation), can also be useful for XRA/XRF-body integration. For example, haptic feedback provided via a vibrator worn on the augmented hand (i.e., task-intrinsic) can improve performance in a hand-robot coordination task[17]. The able-bodied participants performed the task with an XRF attached to their wrist, which they controlled using a switch placed on a worn ring (task-intrinsic kinematic null space). With the sensory feedback, a significant reduction in task completion time and mean force exerted was achieved, suggesting that it helps users learn to efficiently control the XRF with less effort and in collaboration with the biological fingers. Other non-invasive approaches, such as superficial functional electrical stimulation[40], vibrotactile stimulation[41] and transcutaneous nerve stimulation[42,43], can also be exploited in this context (Table 2).

But what if we managed to precisely target the sensory pathways of the nervous system to report sensory feedback from the extra robotic limb? Akin to what was discussed in the motor control section, it is conceptually feasible to build on existing redundancies in our somatosensory system to convey tactile information. This is demonstrated by the use of invasive somatosensory stimulation[35,44,45], showing promising results that are unmet by non-invasive techniques[37]. Such an approach was exploited before[46], by "remapping" a sensory pathway in order to provide position feedback to trans-radial amputees. This and related examples[47] demonstrate that new associations can be formed and sensory signals used to convey new information. But the analogy to the motor domain ends here because, to our knowledge, stimulation of both peripheral nerves and central pathways in the somatosensory system always induces sensations on the biological body. In other words, while it might be possible to control an extra robotic limb using the motor-task neural null space, we do not yet know how to best provide sensations for perceived locations on a non-existing body part. A recent study in upper limb amputees[48] examined the effect of a long term use of artificial tactile feedback that features a mismatch between perceived location and the actual location where sensation arise on the robotic hand (e.g., feedback from a bionic index finger delivered via nerve stimulation and perceived as touch on the phantom-hand middle finger). The authors found that the perceived location of touch was not shifted on the phantom hand, despite the mismatch between the sensor location and perceived location over a long period of prosthesis use. This study provides preliminary interesting findings that the somatosensory cortex may not be sufficiently plastic to accommodate the modulation of sensory information. Conversely, mild changes to the cortical hand representation in the primary somatosensory cortex – and more specifically the boundaries between finger representations – have been found following altered experience (e.g., nerve/digit deafferentation[49,50], increased usage[51], syndactyly[52,53], or mobile phone usage[54]). This likely requires modulation of an existing receptive field rather than remapping[55]. As such, we suggest that daily life experience, afforded by a prosthesis or an augmentation device, could potentially shape the fine-grained aspects of hand representation. Indeed, in a recent study[7], it was found that semi-intensive use of an XRF triggered a change in the motor cortex representation of the biological hand, likely due to the adaptations users made in their inter-finger co-usage patterns in order to extend their motor repertoire and take advantage of the XRF.

It still needs to be investigated whether the inherent sensory feedback is sufficient or if additional artificial feedback, exploiting the sensory complementary space, will be needed. Even though it is not clear yet if users will be able to process additional sensory information in case of increased cognitive load, preliminary evidence seems to suggest that invasive approaches might be more robust in this case[37]. See Table 2 for a summary of current limitations and key enabling principles for the development of future sensory interfaces based on the inherent feedback, sensory substitution, non-invasive/invasive sensory remapping strategies for XRLs. Finally, it is important to emphasize that different types and applications of extra robotic limbs will require different customized solutions for sensory feedback, so a "one size fits all" approach is not suitable.

Regulatory, legal and ethical considerations

Human augmentation via XRAs and XRFs raises societal and ethical concerns that should be addressed, especially by those collaborating to realize motor augmentation as an industrial or household product (Fig. 1). Some of these challenges are not new and have been debated in other domains, such as industrial automation and digitalization[56] or plastic surgery. However, extra robotic limbs increase the complexity of the debate. This is because on one side, there are usage-related risks, ranging from employment considerations to military use. For instance, employing augmented workers could reduce the total number of employees necessary, thus improving efficiency and labour costs but also reducing manual job opportunities and risking high unemployment rates in that sector. Meanwhile, military armies employing augmented soldiers could gain unfair advantages and cause massive destruction. These concerns, however, are transversal to many other technological advances, so future efforts in the field should emphasize ethical and safety considerations to enable a conscious use of XRLs. But on the other side, there are also philosophical and ethical implications to augmenting the natural physical constraints of a biological body. Recently, an ethical framework has been proposed for human augmentation[57], building on previous frameworks for emerging technologies, such as the Transhumanist Declaration, and providing stakeholders with a starting point for discussion.

A broader and fairer acceptance of augmentation technologies also requires international standards and guidelines aimed at ensuring, among others, safety, equity, equality, and privacy[58]. In this respect, a critical step in defining a legal framework for human augmentation was undertaken by the European Union's reform of the regulatory scheme for medical devices, in which the category of "products without an intended medical purpose" was introduced. This includes devices with an augmentative purpose along with analogous therapeutic devices, now better reflecting the enhancement continuum from restoration to augmentation. While this legislation filled a critical legal gap, it mainly deals with safety and security concerns and a unified framework of criteria for permanently or temporarily integrating augmentative technologies with the body is yet to be conceived. From the neuroscience perspective, such criteria are especially important because persistent usage of extra robotic limbs might interfere with a user's biological body representation and potentially even cause disruptions that impair them in daily life[7]. If this is the case, humans may find themselves exposed to new vulnerabilities caused by the very technologies designed to overcome their frailty[59,60]. Since the sensorimotor body representation does not fully mature before the age of around 12[61], children and adolescents could be particularly vulnerable to the impact of these technologies. In sum, the benefits of the availability of augmentation technologies would need to be evaluated against the backdrop of measures protecting its users in general and minors in particular.

Further considerations for successful implementation of motor augmentation

Despite promising results from clinical, neuroscience and engineering research[5,7,62], the field of upper-limb augmentation is still in its infancy and many challenges lie ahead. We consider the need to understand how to effectively implement sensorimotor control of these devices without interfering with the biological body a crucial first challenge. Here, we offered the concepts of "motor task null space" and "sensory complementary space" to help focus the initial discourse and pave the way for innovative solutions to the *"Neural Resource Allocation Problem"*. Notably, each solution has its own advantages and challenges, which will need to be evaluated for the specific usage scenarios of a given technology. As devices evolve for more diverse functions and settings, these issues will become more complex and require more sophisticated solutions (e.g., invasive implants), which should be accompanied by further ethical and legal oversight.

From a practical perspective, if in order to control an extra robotic limb the user has to limit what they can do with their biological limbs, then there is no enhancement of capabilities but rather a substitution. At the early stages of engineering research, such considerations are usually disregarded. However, without clear criteria for assessing XRAs and XRFs as augmentative devices, the formation of a common ground for reproducible research and progress in the field is limited (see Table 1 for the various different outcome measures used). A unified framework is necessary to evaluate any XRA or XRF in terms of the functional improvements it achieves for the specific task it has been designed for and its versatility for more general use. Relatedly, it is important to consider the extent of training needed to proficiently operate the device – will the effort be comparable to learning to cycle, play the drums or use a new touch screen? Device control that requires a lot of mental resources, such as attention, might introduce a cost to augmentation that users are not able or willing to pay. Finally, we need to ask critically whether the reliance on motor and sensory pathways requires the XRA/XRF to be represented in the brain as a part of our biological body? Current evidence is suggesting that the neural body representation may not be malleable enough to integrate extra robotic limbs along with the biological limbs[63,64]. As such, instead of aiming to integrate the XRF/XRAs into an already existing body model, our brains might develop new functionally dedicated representations for the extra robotic limbs. This idea relies on Hebbian experience-dependent plasticity mechanisms and the notion that there are redundancies in our nervous system. By freeing the design of extra robotic limbs from the constraints of the body model, we can aim to achieve 'soft embodiment' of these new devices. This does not entail abandoning the resources that the brain has already evolved, but rather recycling them in a new and better way by taking advantage of the opportunities that non-biological materials and machinery offer[11]. Unlike widespread notions of embodiment, soft embodiment is more liberal and does not require the extra robotic limb to be viewed, perceived or experienced as a biological body part. Ultimately, progress for the emerging field of human body augmentation will not only rely on uniting perspectives and concerns from engineering and neuroscience to create and evaluate better devices, but also more widely on legal and ethical considerations.

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Contributions

GD and SS equally contributed to writing, editing, the overall vision of the paper, and the figures. They wrote the *Introducing robotic body augmentation and the neural resource allocation problem* section. GS and SR wrote the *Sensory feedback for the extra robotic arms and fingers* section. EP and FV wrote *Regulatory, legal and ethical considerations*, AdA and DP wrote the *Motor control of extra robotic arms and fingers*. TM and SM wrote *Further considerations for successful implementation of motor augmentation*. AdA, TM, DP, and SM equally contributed to the overall structure and the underlying idea of the review. All authors reviewed the manuscript.

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		Reference	**Control strategy**	**Sensory feedback**	**Number of subjects**	**Test task**	**Results**
Robotic extra fingers for augmentation	Task-Intrinsic Kinematic Null Space	Hussain et al., 2015[17]	Switch button on a ring	Vibrotactile feedback on a natural finger encoding contact onset/offset or exerted force	10 healthy subjects	Pick-and-place task (20 randomized trials, 5 repetitions for each feedback condition + no feedback)	Haptic feedback improved task performances and was preferred by the subjects with respect to no feedback.
		Lisini Baldi et al., 2020[15]	Dominant arm kinematic recordings	None	10 Healthy subjects	2 tasks in virtual reality (VR): Trajectory tracking and spheres overlapping, and 2 tasks in real environment: Single and multiple objects pick and place)	The control strategy was appropriate to control an extra degree of freedom in VR. Subjects learnt to use the system to perform pick and place tasks.
	Task-Extrinsic Kinematic Null Space	Kieliba et al., 2021[7]	Force sensors under the big toes (1 for flex/ext, 1 for abd/add)	None	31 healthy subjects (20 augmentation, 11 control group)	Behavioural tasks om hand-XF coordination and collaboration, hand motor control, body image, subjective sense of embodiment of the XF. MRI recording pre and post a 5-day training session with 'in the wild' usage	Improved motor control, dexterity and hand-robot coordination with training. Increased sense of embodiment. Modified kinematic hand synergies and cortical hand representation.
	Task-Extrinsic Muscular Null Space	Aoyama et al., 2019[20]	Posterior auricular muscle sEMG interface	Vibrotactile phantom sensation interface on the contralateral hand	1 healthy subject	Timed extra finger opposition task with and without feedback	Learning effect: # successful hits per trial increases. Feedback reduces the average unsuccessful hits ($p < 0.1$)
	Autonomous	Wu and Asada, 2016[65]	Bio-artificial grasp synergies	None	N.A.	Grasping of large objects success rate	The subject can learn to adapt his hand postures to avoid grasping failure with the 7-fingered hand

Robotic extra fingers for restoration	Task-Extrinsic Muscular Null Space	Salvietti et al., 2017[6]	Forehead frontalis muscle sEMG interface. High level control strategy based on #contractions	None	4 chronic stroke patients	Frenchay arm test (measure of upper extremity performance in daily activities)	All the subject increased their score from 1/5 to 3/5
		Hussain et al., 2016[66]	EMG interface embedded in a cap (eCap)	None	6 stroke patients	Frenchay arm test (measure of upper extremity performance in daily activities) and 4 bimanual tasks	All the subject increased their score in the Frenchay Arm test. All managed to accomplish the bimanual tasks without training.
Virtual extra hand for augmentation	Task-Extrinsic Kinematic Null Space	Abdi et al., 2015[67]	Foot movement tracking with depth cameras (MS Kinect)	None	13 healthy subjects	3 games: 1 hand target reaching, 3 hands sliding (third hand opposite to naturals), 3 hands falling objects catching	Use of the 3 virtual hands with no special priority Fast learning
Robotic extra hand for restoration	Task-Extrinsic Kinematic/Muscular Null Space	Ciullo et al., 2020[62]	3 input methods tested: residual grasp force; bending sensor interface on the unaffected hand; trigger controlled by the unaffected hand.	None	10 chronic stroke patients (FMA < 2)	Modified ARAT tasks	Score >13/30 for each patient with at least one interface (excl. dropouts)

Robotic extra arms for augmentation	Task-Intrinsic Kinematic Null Space	Guggenheim et al., 2020[5]	Patterns of fingers pressure	None	N.A.	Door opening and walk through	Successful demo
	Task-Extrinsic Kinematic Null Space	Saraiji et al., 2018[68]	Wearable interface tracking the foot position/rotation and the toe posture	Force feedback to the sole employing a motor driven belt mechanism	12 healthy subjects	One arm pointing task (only with the robotic arm)	Mean throughput of 1.01bit/s No learning over the sessions Agency but not ownership
	Task-Extrinsic Muscular	Guggenheim et al., 2020[21]	Torso muscles sEMG interface	None	11 healthy subjects	Pointing task: minimize position error between targets and limbs (natural and/or robotic)	Performances with natural limbs declined when adding extra limbs (opposite not true) and the four limbs are seldom moved concurrently.
	Neural Null Space	Penaloza and Nishio, 2018[13]	Single channel PSD threshold-based BMI. Relevant channel chosen during calibration (separately for single and multitask)	None	15 healthy subjects	Single task bottle grasping/releasing and multitask which adds a ball balancing task in parallel	Percentage of correct trial is unimodal for single task (67.5% median) and bimodal for multitask (72.5% median). Good performers and bad performers had 85% and 52.5% median correct respectively.

Robotic extra legs for augmentation	Task-Extrinsic Muscular Null Space	Parietti et al., 2017[9]	Sensor suit measuring sEMG from pectoral and abdominal muscles	None	8 healthy subjects	Tracking task: control the extra legs, either in a simulation (exp 1) or wearing the prototype (exp 2) following two targets displayed on screen	The velocity control was identified as the best strategy (compared to position and muscle model) to control the simulated extra legs Both Naive and trained subjects performed better when wearing the physical prototype

Table 1: Summary of previous studies on XRAs and XRFs sensorimotor control and assessment, divided with respect to the type of extra limb and the enhancement category (augmentation or restoration); further categorization considers the motor control approach. All the examples reported in the table satisfy the wearability condition described in Figure 3.

		Existing sensing technologies	**Current limitations**	**Key enabling principles**
Motor task null space	**Kinematic null space**	– Wearable IMUs – Goniometers – Torsiometers – Triggers	– Unknown learning curves – Limited degrees of freedom – Low embodiment of the XRL	– Definition of task-intrinsic and task extrinsic null spaces – Augmented motor synergies – Shared control – Proportional control
		– Force sensors	– Measurement reliability	– Advanced sensing technologies
	Muscular null space	– Surface EMG electrodes	– Unknown learning curves – Electrodes density – Muscle Fatigue	– Portable wireless high density EMG
		– Intramuscular electrodes	– Long-term stability	– Safe minimally invasive electrodes – Wireless interfaces
	Neural null space	– EEG electrodes	– Artifacts – Portability – Poor signal-to-noise ratio	– Filtering techniques – Wireless high density dry EEG
		– ECoG arrays	– Safety – Long-term stability	– Soft neural interfaces – Low-power implants
		– Intracortical electrodes		
Sensory complementary space	**Inherent feedback**	– Wearable extra limb-body interface	– Limited conveyable information	– Target sensitive body parts – Rigid interfaces
	Sensory substitution	– Headphones – Haptic displays	– Cognitive load – Obstrusive – Non-intuitive encoding strategies	– Soft embodiment
	Sensory remapping	– Haptic displays		
	Invasive sensory remapping	– ECoG arrays – Cuff electrodes – TIME electrodes –	– Safety – Long-term stability – Technology readiness level – Somatosensations from non-existing body part – Cognitive load	– Soft neural interfaces – Multi-channel stimulation – Low-power implants – Soft embodiment – Advances in new-conventional stimulation approaches

Table 2: Current limitations and key enabling principles of the existing technologies to develop bidirectional XRLs control exploiting the motor task null space and the sensory complementary space

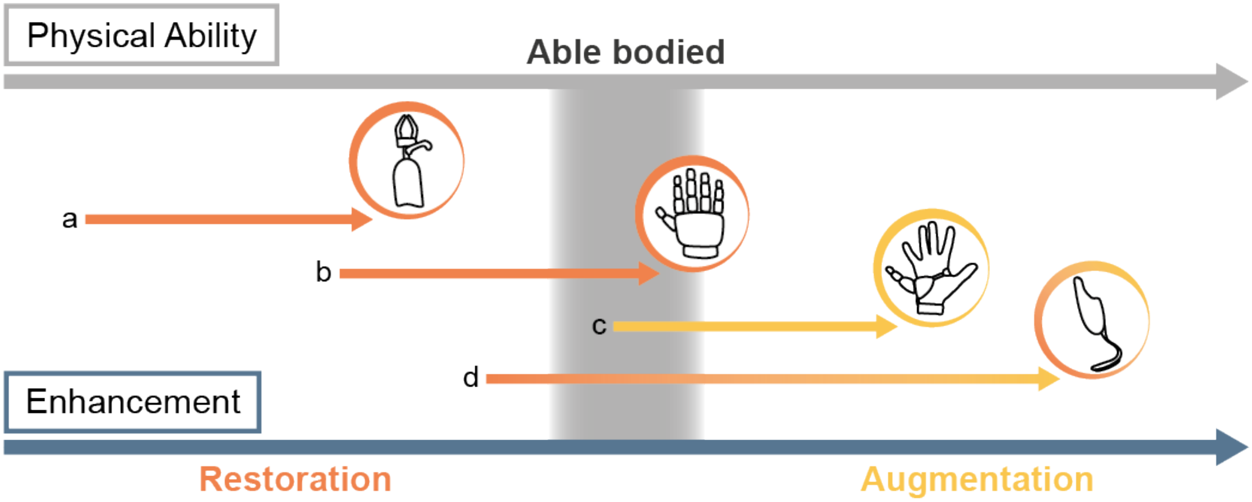

Figure 1: Body enhancement continuum with respect to bodily ability. . The partial (**A**) or complete (**B**) restoration of a function (e.g., reaching and grasping) in a subject with a given initial level of impairment (amputation) with a hook and a polyarticulated motorized robotic hand respectively. (**C**) The enhancement of able- bodied subjects for a given function is defined as augmentation. (**D**) The enhancement of a subject with disabilities beyond the capabilities of an able body is also a case of augmentation; here the example of a running blade prosthesis. Examples of restoration of a function are reported in orange and augmentation in yellow.

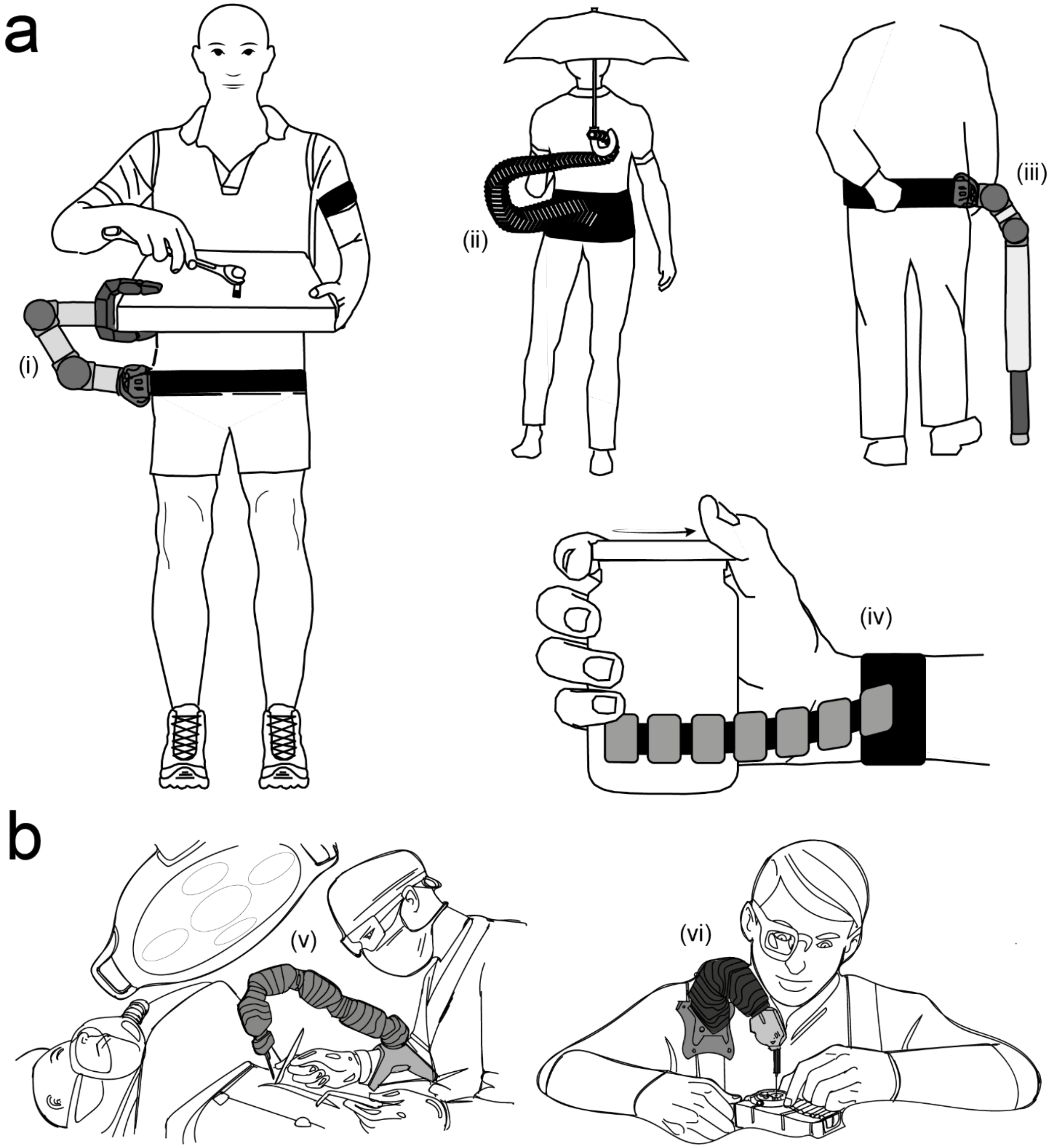

Figure 2: Examples of use case scenarios of body augmentation with extra robotic limbs. (**A**) Examples on the basis of the current state of the art. (i) an extra robotic arm helps with holding and screwing simultaneously; (ii) a robotic tail holds an umbrella freeing the user's hands; (iii) an extra leg helps an elderly user walk;(iv), an extra robotic finger helps stabilize the grip while opening a jar with only one hand. (**B**) Possible use scenarios for the future of extra limbs in medical (v) and industrial (vi) applications.

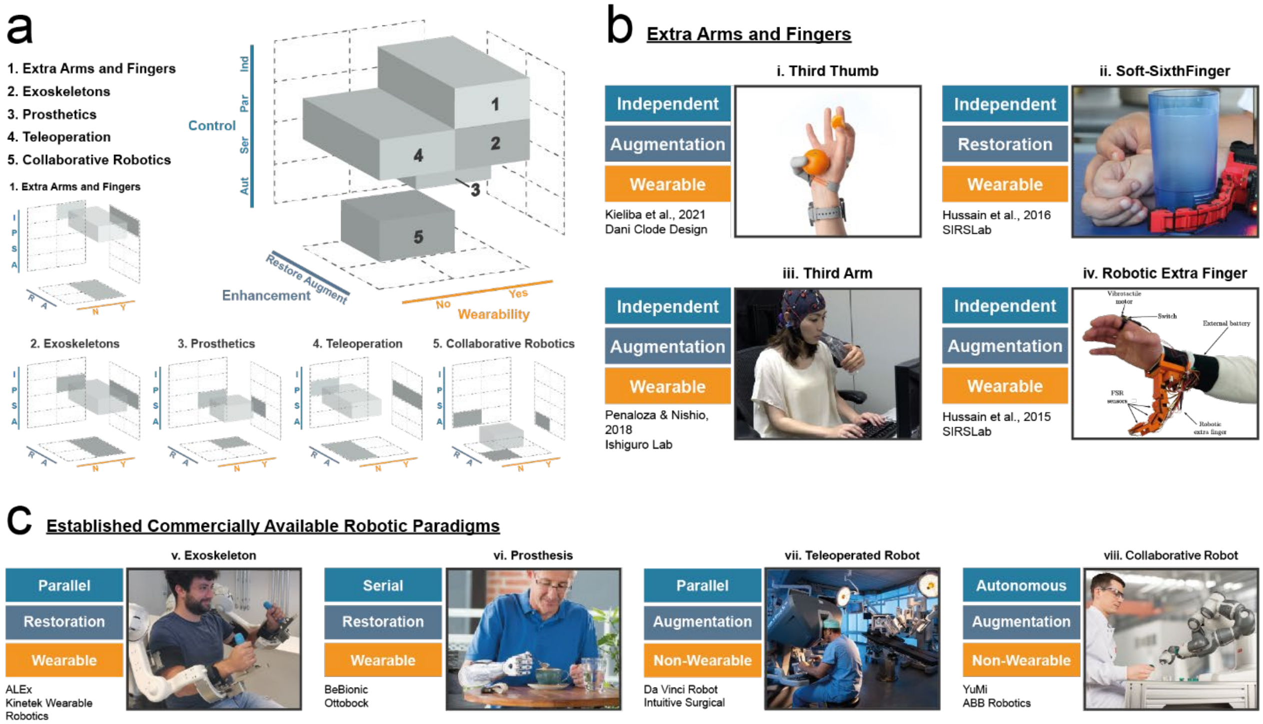

Figure 3: Taxonomy for extra robotic arms and fingers and comparison with established robotics paradigms. (**A**) Three-dimensional space defined by control strategy, enhancement, and wearability. **Control** (blue) is defined with respect to the natural upper limbs' joints: robotic devices can be controlled (Ind)ependently from the user's upper limbs, in (Par)allel by mirroring the user's biological limbs, in (Ser)ies by extending the kinematic chain of the biological limbs or they could be entirely (Aut)onomous. The **Enhancement** (gray) is divided into two categories: restoration (Restore) and augmentation (Augment); **Wearability** (orange) defines whether the device is meant to be worn (Yes) or not (No);

(B) Examples of XAs/XFs with their corresponding description for control (cerulean), enhancement (gray-blue), wearability (orange). (i) The third thumb (Dani Clode Design – daniclode.com, image reproduced with permission), is controlled using force sensors strapped underneath the participant's big toes[7]. (ii) The soft Sixth finger is an extra finger used for the restoration of functionality in stroke patients[66]; the finger is controlled via decoding of muscle activation (image reproduced with permission from Domenico Prattichizzo, SIRSLab). (iii) A healthy subject can control a human-like robotic arm for multitasking, using an EEG- based brain-machine interface[13] (image reproduced with permission from Advanced Telecommunications Research Institute International). (iv) The robotic extra finger is controlled via a switch on a ring; the same ring provides vibrotactile feedback to the user[17].

(C) Representative examples of classes of established robotic paradigms. (v) The ALEx Upper-limbexoskeleton, for hand therapy (Kinetek, Wearable Robotics, Ghezzano, Italy). (vi) The bebionic prosthetic hand for transradial amputee patients (Ottobock, Leeds, England, image reproduced with permission). (vii) The da Vinci robot is a tele-operated surgical robot (Intuitive Surgical, Sunnyvale, USA, Robot Da Vinci in Hirslanden Clinique Bois-Cerf, Clinique Cecil, photography by Loris von Siebenthal). (viii) YuMi robot permits safe collaboration between the user and the robot (ABB, Zurich, Switzerland, image reproduced with permission).

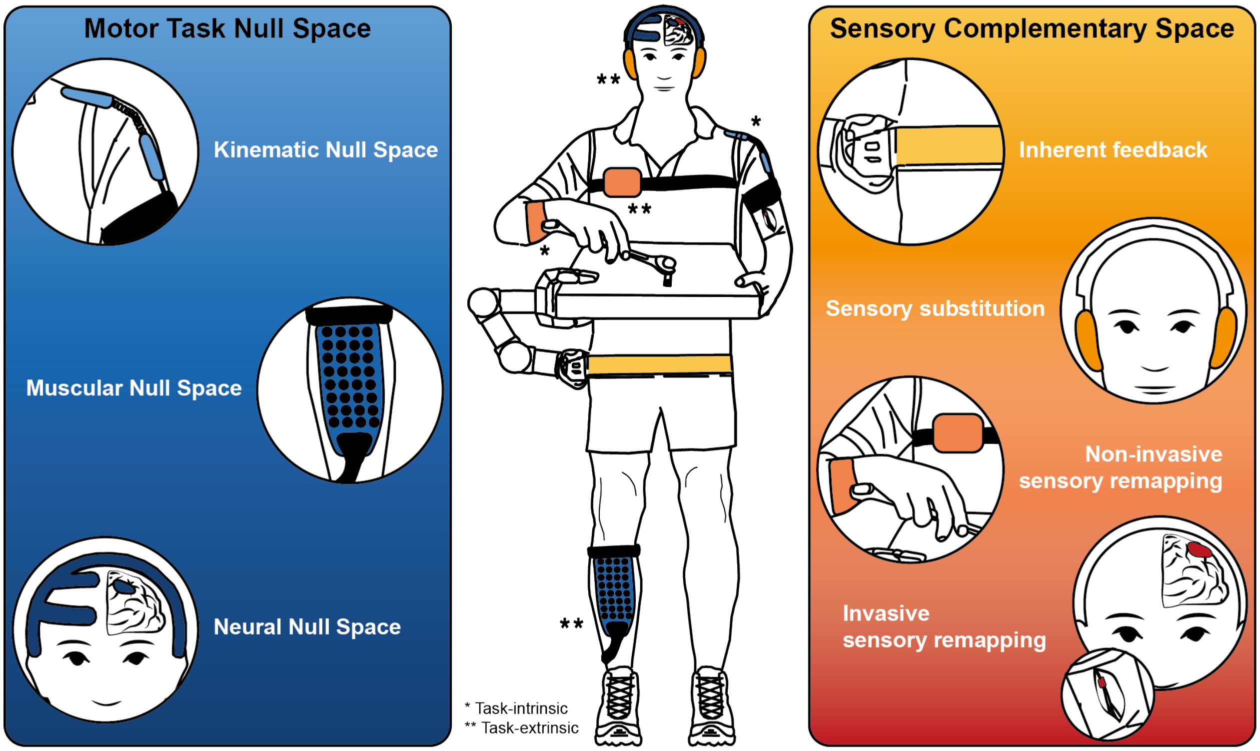

Figure 4: Possible interfaces for control and sensory feedback for an XRA. [**Left**] examples of recording from the kinematic (light blue), muscular (blue) and cortical (dark blue) motor task null space. [**Right**] examples of sensory complementary space via inherent feedback (yellow), sensory substitution (light orange) and non-invasive (dark orange) or invasive (red) sensory remapping. One asterisk denotes task-intrinsic implementation while two asterisks denote task-extrinsic ones. Asterisks indicate whether the interface is task-intrinsic (*) or task-extrinsic (**).