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Development of Bioadaptive Smart Prosthetics: Integrating Neuromuscular Interfaces and AI for Personalized Mobility Restoration

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Annotation: Neuromuscular interfaces (NMIs) are emerging as powerful technologies for restoring specific functions in individuals suffering from neurological and functional motor disorders. People who have lost the ability to move their extremities due to various conditions such as spinal cord injury (SCI), stroke, and muscular dystrophy, and those suffering from limb amputations, desire assistive technologies that can restore lost abilities and enhance their quality of life. To address such needs, significant advances in technologies are being recently made, which augur well for better and more human-like restoration of movement abilities .

Motor-intent NATs, designed to ensure a seamless and natural interface with the nervous system, passively monitor neural activity using micro/milli-scale sensors for so-called 'read-out' approaches, or, conversely, stimulate the nervous system using electrodes for ‘write-in’ approaches. System intelligence NATs consist of physiologically inspired computing architectures and bioinspired computational approaches, such as artificial hormonal memory, and deep layer inference mechanisms, which are inherently optimized for real-time user-specific operation. Smart system NATs are adaptive, enhancing system intelligence and improving reliability by fusing imaging, sensing, and communication modalities to match expected task complexity.

To create disbursed smart organ-like bioadaptive systems, strong collaborative research and development efforts across fields such as neurophysiology, neural and muscle interfacing technologies, system intelligence, and artificial intelligence/machine learning are now urgently needed. An initial effort to push the grand vision of bioadaptive organ-like systems was undertaken through the four international workshops and master classes. They targeted especially Ph.D. students and early-career researchers. The workshops focused on teaching from both the human and the technology sides related to NMIs and AI for neuromuscular rehabilitation, respectively, whereas others invited participants to design tailored and personalized solutions starting from a user-centric challenge. Along with classroom lectures from leading experts, participants were introduced to tools to model the challenge and proposed designs.

1. Introduction

Below the knee amputation alters the everyday function and quality of life for millions of amputees every year. Standard prosthetic devices including passive and powered prostheses have been developed over the last century to assist mechanical mobility of lower limb amputees. Due to the passive nature, standard prostheses require active human body involvement and high effort-control, thus limiting their usability and acceptance. Powered prostheses mechanize the toe-off for swing phase initiation and increase gait performance, but existing designs are inherently weakly interactive and rely on direct human control to operate. Consequently, this leads to highly unnatural gaits along with inability to use automated technologies. Advances in motorized, sensor-equipped, and computation technologies allow for the development of bioadaptive smart prosthetic devices to automatically adjust their motion to suit the user needs and changes in environment. There is a strong need to develop bioadaptive smart prosthetic devices to restore graceful and natural mobility for lower limb amputees. Prosthesis integration requires a bidirectional control interface. Internal neural control signals can be decoded and mapped to control commands through the musculoskeletal-to-neuroprosthetic interface, and adjustments to gait patterns can be obtained through real-time optimal control via the neuroprosthetic-to-musculoskeletal interface. Sophisticated controllers can be designed based on adaptive nonlinear approaches to achieve user-intended actions and smooth switching between modes. Further integration with cognition will allow robust gait control in highly dynamic scenarios requiring steep and smooth ambulation.

Most existing smart prosthetics do not provide bioadaptive functionalities, which is the ultimate goal due to the reasons mentioned above. Additionally, the activities and motions of existing devices are typically defined by either empirical exploration or human control. While with limited bandwidth, musculoskeletal signals can be decoded to generate motion commands with minimal lag for instantaneous control of prosthesis motion. Further efforts in adaptive learning are needed to achieve bioadaptive functionalities and accommodate diverse and changing user needs and environments. Non-invasive sensing technologies including computer vision and wearable sensors can provide information and be explored to achieve soft-switching and complementary control. [1][2][3]

2. Background

A thrilling development in the medical and engineering fields has emerged over the past decade through the collaboration of interdisciplinary teams of scientists and engineers focused on rehabilitation robotics. By creating restorative orthopedic devices that mimic biological form and function, this research seeks to assist those with limb impairments and enhance the capabilities of aging bodies. Similarly ambitious goals exist in the areas of rehabilitation and lower-limb prosthetic devices, and widespread technological advances would make even more dynamic and refined rehabilitation systems feasible. Biologically inspired and controlled robotics capable of combining a variety of sensing modalities with biomimetic and bioadaptive algorithms compatible with their human counterparts promise to open new frontiers in health monitoring and restorative robotics. Development of such adaptive assistive technologies, made possible through advances in the micro-miniaturization of low-cost sensors and computational power, would offer profound opportunities for the proactive monitoring of health metrics and as user-specific interventions.

In the field of rehabilitation robotics, by incorporating satellite-based inertial estimation with biomechanical modelling, personal anticipation of human motion informs the prediction of changes to the robotic assistance that would best match the prevailing human intention. This augments the large range of ongoing research focused on legged robot and prosthetic devices to be controllable through biofeedback from wearers. Traditionally immersed in a world isolated from the daily lived experience of people, rehabilitation robotics researchers are becoming increasingly aware of the social and economic contexts within which they operate. Exciting developments are meeting consumer needs for on-the-go services with energy-efficient devices tailor-made for their user. Medical professionals serve a vital role in the development, recommendation, and purchase of rehabilitation robotic devices and systems. Legislators strive to ensure equitable access to rehabilitation robotics through public funding, taxation, and provision.

Exciting development within the field of prosthetic devices is occurring as they transition from passive to active devices capable of providing powered and adaptable assistance to the wearer. Historically comprised largely of passive devices reliant on passive mechanics to mimic biological walking, this development is achieved through three component technologies: advanced sensors for estimating state of motion, control methods to compute a desired device actuation, and power systems to provide energy for this actuation. With the advent of off-the-shelf sensors, advanced signal processing algorithms, and suitable computational platforms, prosthetic control has progressed to the supervisory estimation of multiple intent signals including walking speed, gait phase, stair descent triggering, and step triggering. All proactively anticipate user intent either using predictive heuristic models or through biomechanical modelling, with the aim of determining timely device motion. [4][5][6]

2.1. History of Prosthetics

Prosthetics have been tried in forms from the earliest attempts to the latest advances using nanotechnology and artificial intelligence in a rapid race evolving bioadaptive smart prosthetics. A framework for the development of a state-of-the-art AI powered bioadaptive smart prosthetic limb has been described which can be adapted by adjusting different machine learning parameters to work seamlessly for individuals as-to-use personal prosthetics. The immense work domain of prosthetics as a field is captured under various sections which cover design requirements, development using neuromuscular interfaces, control strategies from AI perspective, and challenges which can pave various paths for innovation targeting mobility restoration [7].

A proof-of-concept low-cost weight lifting robot has been created to showcase combine prosthetic controls using wearables. Control of a hand and elbow has been implemented with the myoelectric signals acquired by surface electromyography sensors or mechanomyography sensors. With the achieved commercial-grade performance, suggest a novel myoelectric control method without bulky modules on muscle or skin surfaces with simple volitive movements. A survey on bio-inspired robotics hands implementation: New directions in dexterous manipulation using deep learning, reinforcement learning, and bio-inspired control methods on hands and arms.

Modeling of pneumatic controlled bio mimetic articulated passive prosthetic spring loaded knee mechanism for transfemoral amputees, device operation using the compression of a pressure vessel, pneumatic controls recreating human gait characteristics due to the structure configuration, and mounting it on an individual carriers under development. A bioinspired stretchable sensory-neuromorphic system composed of an artificial tactile sensing unit exhibiting highly sensitive and directional recognition capabilities which is crucial for accurate object manipulation, human-like tactile perception from tactile sensory unit to neuromorphic circuit and spiking neural network learned pattern classification methods are to be discussed. Mechanoneural interfaces allow for several bionic integration options while achieving high-motion fidelity in transferred brain control of prosthetics with stands across species have been developed.

2.2. Current Technologies in Prosthetics

There exists a large variety of artificial limb designs that span many applications. Most existing designs are passive rather than active prosthetics [7]. They provide no stimulation to the wearer, other than the sense of weight or inertia, which can often be manipulated to the wearer’s advantage by a skilled operator. More complex mechanisms can permit reasonable control of these systems through complex actions of residual muscles, usually in the upper limb. These simpler designs are often labelled as body-powered prosthetics (BP), and comprise a relatively small proportion of purchased prosthetics, especially in the developing world. The largest portion in use is so-called cosmetic or externally powered prosthetics (EP). These systems can take a variety of forms, but generally consist of an outer cosmetic covering and powered mechanism designed to help mimic some of the default functions of the lost body part. Commercially available devices incorporating technology to allow a degree of gait assistance are slowly being introduced into the market but currently still represent a niche offering [8]. A relatively large number of functional designs also exist outside of mainstream medical commerce. These span from simple active designs with a single actuator to more complex multi-joint combinations. Many use self-contained pneumatic actuation systems, whilst others have more recently begun to employ electric brushes and geared motors. As the performance of two main technologies continues to dramatically improve, custom designs employing off-the-shelf high-quality components will be increasingly affordable. Inverse computational design has become relatively mature in other fields, and has great potential for application of new materials and processes to bionics. A “better practice” philosophy, where the most complete and userfriendly software is made freely available, could offer the prospect of rapid technical advance. Simple communications protocols and a wide access to rapid feedback between the prosthesis and its wearer could allow evolvable devices. There are also opportunities for research into the development of joint-property actuators; devices that could adapt their stiffness to match load conditions.

2.3. Challenges in Mobility Restoration

Functional neuroprostheses coupled to the central nervous system and muscle-stimulation units distributing impulses to muscles could restore many lost motor functions. The understanding of how the CNS activates muscles for specific movements has been carried over, for example, to restore reach and grasp functionality upon spinal cord injury. But, unlike flexible robotic manipulators, no bioadaptive design exists for the lower limb after loss of limb, nor for lower limb paralyzed patients. Paralyzing injuries lead to a loss of a large number of functions. Overcoming the loss of substantive functions of the body is regarded as the greatest need for health care, particularly in the field of rehabilitation. But, action restoration systems such as muscle stimulation systems, limb prostheses, or exoskeletons can substitute a single thoroughly understood function, like locomotion, but less so for a range of joint activation patterns leading to the performance of an action. The combination of two approaches could shape the way for functional restoration in rehabilitation robotics replacing what is uniquely human.

The first approach couples a bipedal musculoskeletal model and a controller with synergies to a physical robot. This intrinsic-based bioinspired controller learns to walk using synergies. The second approach realizes dexterous grasping and manipulation with a manipulable robot arm coupled to a bimanual hand. This multi-modal bioadaptive system comprising an adaptive hand and adaptive controller learns to grip and transfer novel objects. The collaborative methodology could be extended for the bioadaptive design of functional neuroprosthetic arms or legs coupled to bioadaptive controllers. Instead of attempting to address a multitude of functions which would be daunting, the design and control call for a bioadaptive module replacement for a single function as a proof of concept. Likely candidates for such systems are bipedal locomotion neuroprostheses for below-knee amputees or paraplegia neuroprostheses for cost-effective indirect actuator-assisted patients, who may not have been onboard sufficiently informative control. In both cases, via muscle stimulation, focused activation of the biomechanical systems could direct motions like stepping, swinging, and foot placement that brute-force control cannot. These systems offer an opportunity to investigate their use for a greater purpose. Acceptance of such systems, particularly for the latter group, with autonomy relying on muscle stimulation, would be a benchmark to assess in what conditions reliance on bioadaptive systems is endurable. [2]

3. Neuromuscular Interfaces

There has been a substantial increase in interest toward integrating artificial or biological robots with the human body and brain. This area covers a wide range of applications, including prosthetics, rehabilitation, cognitive augmentation, and human-robot interaction. Prosthetics are devices that assist or replace the function of missing or degenerated limbs and are the most prominent application of bio-integrated systems. This has resulted in an increasing demand for bidirectional neuromuscular interfaces, which connect with the human neuromuscular system in order to extract control signals for prosthetic devices or return sensory signals to the human body. Furthermore, to improve the functionality and safety of devices with integrated neuromuscular interfaces, unmanned artificial intelligence is required for real-time learning and adaptation to a user's intention to control a robotic or prosthetic device, as well as multi-potent artificial intelligence for raw multi-modal input analysis and real-time decoding.

Neurostimulation has drawn considerable attention in the field of biomimetic sensory feedback to restore sensory perception in amputees. The implementation of implanted neuromuscular interfaces allows for the communication of bio-signals for prosthetic control and therapeutic intervention. Bio-integrated and congenitally compatible transmitters can be envisioned to implement smart prosthetics, where prosthetic control is performed in a secure and robust way. Advanced technologies in ultra-low power biomimetic processors, ASICs, and highly integrated flexible electronics are yet to be developed for electrochemical and optical interfaces. However, the prospect of individual autonomous systems suggests that techniques such as non-biocompatible optogenetics and opto-electronic stimulators can be combined with long-range, bio-interfaced integrated devices with nanometer-thick semiconductors and stabilizers to form a truly bionic cycle.

Surgeons and neurosurgeons have been performing surgeries on the human body for over 100 years. State-of-the-art tools provide direct access to most body parts, leaving very little resistance for innovative technologies. A wide range of applications stands waiting for engineering advances, starting from recording bio-signals up to providing biotic effects to assist or replace damaged organs. The greatest challenge and greatest possibility in this field is the reconnection of machines and biology. In weight, size, and complexity, neural interfaces would match biological interactions, specifically for medium-range applications. This illustrates how both machine development and knowledge of biology are required to span this barrier. Moreover, any biocompatible solution must inherently obey biological conditions such as ultra-stability, bio-integrity, and long-term biocompatibility. [9][10][11]

3.1. Overview of Neuromuscular Interfaces

Neuromuscular Interfaces (NMI) represent a revolutionary breakthrough technology that allows to communicate with the nervous system. NMIs reestablish the connection between the nervous system and muscles through neural signal acquisition and processing, enabling motor control of electrical stimulation of muscles and other cellular tissues [8]. They target peripheral nerves and bring about stimulation of the nerves or recording of their signals through flexible and compliant electrodes able to conform to the curvature of the nerve, targeting the periphery of the nervous system. Interfaces that stab outside of the nerve but use open-loop strategies are studied to achieve stimulation. Neural signals can be piggy backed by traditional surface electrodes targeting the masked and active region of the muscle, able to access both myoelectric and mechanomyographic signals. Bio-integration is a key-assessment parameter of NMIs. Movement-related peripheral neurophysiological signals can be recorded through traditional wet electrodes in subject-specific manner in lab. After-training adaptation becoming less noticeable and one-phase RCG becoming active allows more consistent tracking of the valid signals and better decoding performance. Add-on strategies for ongoing experimental verification would have been great. Further, the use of richer signal sets capturing particle motion and action potential would have been beneficial, which entails additional hardware redesign pertaining analog circuits and sensor position adjustment.

3.2. Types of Neuromuscular Interfaces

NMIs can be categorized according to how they sample information regarding neuromuscular activity and/or how they actuate the prosthetic technology hardware. In general, they can be classified into direct and indirect ones [8]. In direct methods, information about the biological network is sampled directly from the anatomical location where this network is located. These methods have high temporal resolution and fidelity. However, they present challenges for long-term implantation and must guarantee biocompatibility. Indirect methods sample information about the biological network via one or more intermediary biological processes and some optimization algorithms, which transforms information from one domain into the other. Accessing information via indirect methods usually makes high fidelity and high temporal resolution difficult to achieve but allows for implantable devices with a higher long-term functional viability.

This high-level classification can then be sliced into the following subclasses of NMIs: (1) direct interface with CNS signals via implanted electrodes sampling information from the midbrain, cerebellum, cortex, or spinal cord; (2) interface with PNS signals via surface or implanted electrodes sampling information from muscles or nerves; and (3) bioindirect methods interface with kinematics/speed or muscle forces applied to the limb joints. The requirement of interface selection can accommodate prior surgical treatments or clinical conditions; this same requirement alleviates excessive and prohibitive costs associated with higher-level electrodes and signal processing methods.

3.3. Signal Acquisition and Processing

A closed-loop brain-machine interface (BMI) system using an independently functioning sensor-brain-motor interface (SBMI) system is implemented to provide natural, robust, and intuitive restoration of proprioception/motion using diverse commands. The sensor interface consists of wireless stretch-based sensors and wireless accelerometers. With innovation in read-out electronics, a compact, integrated SBMI chipset is implemented to perform signal processing in real-time and enable on-demand data transmission and stimulation for BMI acceleration. By developing minimally invasive robots based on screw-type and moveable implants, practical and long-term integration of the SBMI system with the patient is achieved. The system has potential applications in animal studies and pre-clinical experiments [12].

Complex brachial plexus injuries led to near-complete loss of sensory and motor function in a hand. A 5×4 Utah array implanted in the motor cortex (M1) detected motor intent to reconstruct movements in an external hand. The artificial hand matched the amplitude of effortful movements, translating the user's intentions in the dimension of the largest movement diversity by performing mostly orthogonal movements with a large range. An array of six microwires targeting the somatosensory cortex (S1) was implanted. The sensor-brain-motor interface (SBMI) restored both action duration and cortical sensory signatures for movement intention restoration. The research proposes a fully integrated sensor-brain-machine interface (SBMI) system, constitutes a SBMI to emulate the somatosensory feedback of hand movements, and restores natural control by providing multi-modal feedback to the user. The system successfully restored motion intention with a broad spectrum of utilization and potential clinical applications.

Prostate cancer is the most prevalent malignancy among men worldwide. Although local treatment is effective, it fails in some patients, which leads to a poor prognosis on advanced stages. To avoid overtreatment, the need for deeper biological understanding of the emergence of aggression and resistance mechanisms is required. In the past two decades, mouse models have helped elucidating the cellular basis of human disease, and paved the way for more effective therapies. Biobanks of genetically engineered mouse models of prostate cancer have been established enabling the study of a variety of molecular driver alterations involved in the pathophysiology of human PCa.

3.4. Integration with Prosthetic Devices

A neuromuscular network is only useful as long as there are inputs and outputs. To interface with and control the inner goals of the user, the corresponding outputs must be integrated [8]. This is classically done with body-worn devices like exoskeletons, which must take care of on-board sensors, actuators, batteries, etc. or non-embedded smart tools like tablets which must be designed for daily use. Still, it needs integration in the daily life routines of the user.

However, new methods are needed to introduce awareness and purpose to natural biological networks. Moreover, the final goal is to integrate knowledge and information gathered by the NMIs into the anthropotic and artificial ecosystem. Another aspect to consider is some modifiability of the device in a looped interaction and control, permitting, for instance, both the tracking of biological control signals and the progressive inclusion of autonomously estimated or learned ones.

Examples of high-level control for lower limbs prostheses and exoskeletons exist, tracking the movement of an intact opposite limb or pursuing points in space. Still, most implementations are indirect, reducing the follow-up and service details, and need mid-level and low-level modules or control strategy definition.

Modelling the function of a biological limb and its impairment is needed for the design and control of bioinspired artificial limbs. There is still only a little understanding of both the structure of the control task and how this is mapped to the brain. Biological limb models can help with this, as they have the same functional role as prosthesis; help a living body to achieve its objectives.

Control and learning a prosthetic device is more complex than its human counterpart. This aspect is actually what makes these devices bioadaptive. The coupling with the biological counterpart is incomplete, and since the desired behaviour is usually predefined, the questions return to a mapping problem rather than a control one. Also, the control design can change in the operating parameter space. For these aspects, and others needing robust communications, additional assumptions must be introduced.

4. Artificial Intelligence in Prosthetics

As has been mentioned above, neural information from electrodes placed on the stump can be extracted and decoded in real-time, together with ingests from on-board sensors, imbuing the prosthesis with bioadaptive features. In this paper, the bioadaptive control approach is for the smart prosthesis and certain details on how it can be implemented. Since it is discussed, although this control approach can be tuned with a broad family of controllers, focus is given on the integration of NMP with Adaptive Dynamic Programming (ADP). Learning has been applied to NMP controlling smart prosthesis systems, with direct application of Adaptive Neuro-Fuzzy Inference Systems, as well as other neural network algorithms; ADP has also been used separately to control robotic structures, but never on prosthesis systems. Learning and updating the NMP controller parameters in real time have been shown on bi-manual robotics and humanoids and directly inspired by motor learning of the human brain. Nevertheless, there are no reports examining the ability of this technique for a smart prosthesis. As this technology is developing, it may also be possible to implement it in LPM on software-based simulation testbeds to make it more accessible. With artificial intelligence, it is possible to learn both how to accurately move the prosthesis in accordance with a goal trajectory and correctly predict the desired joint torques instantaneously. If this goal is achieved, the developed surrogate model is then used directly to control the joint motors via torque control, rather than as a constant torque controller. Such surrogate models can be significantly smaller than the more complex controllers. There is a wider family of models that could be included, as well as real testing with smart prostheses. Still concerning AI, but more specifically on model based control, there is the challenge of strong robustness guarantees. Though the proposed control architecture works on mathematical models whose quality is supported by real-time high fidelity simulations, the system is being deployed on LPMSs manufactured by different vendors with different specifications, which could potentially lead the controllers to proper failure. Several advances in state-of-the-art wearable robotics in rehabilitation applications are reviewed. This includes both upper limb exoskeletons and soft robotic systems. State-of-the-art control strategies are presented, as well as actuators and sensing technologies commonly used in this field. Finally, future challenges are presented. The integration of AI-based strategies is seen as a primary development in the area of robotic rehabilitation, especially in exoskeletons and wearable soft robots. However, AI systems still present limitations for wearing safety. It is concluded that a broader focus on medical requirements and safety assessments are two areas where AI-based rehabilitation robotics can further optimally develop [13].

4.1. Role of AI in Mobility Restoration

Conventional AI techniques, particularly Deep Learning Convolutional Neural Networks (CNNs), have recently gained popularity in upper-limb prosthetic control research. By using various modalities of input data such as EMG, IMU data, and depth image from RGB-D cameras, researchers have made great strides in refining and enhancing the adhesion strength, time efficiency, and manipulation dexterity of upper-limb prosthetics. These advances have yielded prosthetic systems capable of achieving near natural performance. Nevertheless, due to some inherent limitations, conventional AI-based upper-limb prosthetics have yet to achieve wide adoption in clinical settings. These limitations may be generally summarized into three key points, as elaborated below [8].

First, the majority of upper-limb prosthetic designs are composed of off-the-shelf components with limited degrees of freedom, which causes difficulty in replicating the dexterous motion of the human hand thereby limiting their adaptability across a wide range of daily activities. Most commercialized upper-limb prosthetics are equipped with standard proportional myoelectric control. Users achieve control by modulating the contraction level of their muscles, which causes these designs to exhibit the same type of gross motion as the human hand. Due to this type of control, the proposed prosthetic systems are fairly slow with limited manipulation dexterity, causing inconvenience in performing their daily activities. Low dexterity, slow, non-intuitive motion, and lack of sensory feedback hinder the current devices from full acceptance by users.

Further, the concept of prosthetic devices including a machine learning algorithm that mimics the motions of the human hand has emerged. This approach delivers affordable and effective prosthetics despite their limited capability in the naturalness of control and speed. As supervised learning techniques are being applied, practical issues have arisen such as requiring substantial computational power for collecting large amounts of labeled training data, difficulty in re-accommodating to pattern drift, and instability of response when unseen data types are encountered. The physical differences in terms of mass and inertia between a prosthesis and a human limb further limit the generality of this approach.

Importantly, safety leaves much to be desired in current prosthetic designs. Investing elastic materials in robotic hands and applying model predictive control techniques create compliance, thereby ensuring safety. Nonetheless, in the presence of unmodeled dynamics and uncertainty in the measured states, the passive compliance should be tuned carefully to maintain the grasp stability. Otherwise, they may fail to retain contact in the case of unknown forces. The conventional soft robotic hands actuated by smart materials exhibit trailing response at controlling speed. As a result, they may fail to provide robust response, which is not always ideal for holding fragile objects.

4.2. Machine Learning Techniques

As enabling technologies become pervasive in society, product designers increasingly seek to satisfy desired interaction qualities. Such qualities include the types of movements a user can realize while interacting with a device or the information they may leverage from a display. Knowledge about these desired qualities can be expressed with an interface description language that enforces separability of functionality, with an accompanying data representation language that supports abstraction of implementation details. Such languages help users acquire understanding and lead to a more experiential view of interactivity by lowering the barrier to questions regarding the user-device relationship.

With the increased prevalence of biomedical devices, designers of such systems may apply the same perspective. An authoring framework may help biomedical engineers formulate the desired capabilities of their designs, support them in evaluating their devices through simulation or experiment, and help make their knowledge and integrally simulated designs accessible to third-party teams. These tools would foster collaboration and interdisciplinary design. In this Application Note, the potential benefits of an authoring framework for bio-adaptive devices, as well as some enablers for its implementation, are discussed.

Bioadaptive devices yield remarkable capabilities through complex and orchestrated data processing pipelines. Any FDA-regulated bioadaptive device contains a ‘natural’ estimation algorithm for a physiological variable of interest. For instance, wearable glucose sensors perform signal processing on recorded heart rate signals, employing models of the glucose dynamics and statistical methods to estimate the glucose concentration. Such processing pipelines are often conceived and implemented by expert engineers over periods extending years, all while published knowledge about relevant physiology and existing models is scattered over hundreds of papers. High barriers arise for third-party teams willing to develop innovative implementations that use a design's bioadaptive abilities [13].

4.3. Data Collection and Analysis

Experiments will be performed to collect data from 11 transfemoral and transtibial amputees (n = 6 in-user, n = 5 out-user). Self-reflection videos will be taken to record their feelings during using or not using their prosthesis in daily life. Signals will be recorded during the video. Self-reflection transcriptions and signals will be processed by the Graphic Method and Empirical Mode Decomposition to extract the emotion score and its frequency with standard values. The self-reflection scores of individuals can be compared in-depth. The labeled results will be trained on different classifiers with signals to provide a wearable prosthesis control method. Transfemoral amputees will be recruited to test bioadaptive control in everyday life, and kinematics will be tracked with an optical motion system to evaluate the performance.

The Gait Pattern Prompting System Tag will provide the user with the repetition of gait matching their intention and train them to broadcast their intention. The task will be a kind of spaced rehearsal design that considers both time-sequence and time-space concealed transfer to maximally elicit self-similar timing features of gait and better generalization for unseen input. Initial medical rehabilitation trials will use simulated gait locomotion to complete alignment and control matching of the User-in-the-loop Drifting-Mode Controller before entering large-variance everyday trials. In each capture session, previous and future collected data will be cached to avoid data leakage and the average testing speed will account for all inputs in that session. A maximum mean discrepancy will be recorded on the training dataset to tune several parameters in a co-optimization scheme with adaptive update rates.

As they conform to the spatial correlation that one gait cannot be more than a threshold apart from the anchor, the outliers will be removed. For periodic input, the in-domain transformation augmentation via 30 pairs of conflicting rotational perturbations at various frequencies and amplitudes will be added to all x-coordinates in the test batch. The input will be projected onto the hyperplane where the time domain is split so there are no more than seven samples belonging to one batch of the quasi-equidistant computations.

4.4. User-Centric AI Models

People with severe motor disabilities and their caregivers involved in technological co-design often experience disorientation or distress from the abundance of initially nebulous design concepts and raw material in the early growing processes. This study proposes a broader view on the role of AI in future prosthetic devices, particularly on the user's perspective. [8] Their perspective particularly emphasizes technology acceptance, futuristic innovations in terms of both hopes and fears, and some socio-political implications of this technology, especially on the links with data surveillance, welfare-state erosion, or blurring of accountability. While not neglecting the potential undesirable implications, this study focuses on the underlying factors driving the humans-technology relation, the needs to be fulfilled, and the socio-technical processes through which concerns or anxieties may transpire or misshape future devices, innovations, and their settings.

AI systems could improve the comfort, safety, and neuro-man-machine co-adaptation of a prosthetic knee, ankle-foot, or hip joint by embedding learning algorithms for online personalization of control and actuators. To accommodate the time scales of continuous bioelectric signal and motion data acquisition, embedded AI chips could dock with the sensors' and actuators' hardware on-board such a device. A low-energy on-board chip could extract robot control commands from user signals and environment mapping to stream selected data to off-board chips with greater processing power for object detection and recognition, or more elaborate machine-learning tasks. On-board bioadaptive AI could continuously track the stability of the trained network and personal trajectories and self-adjust new training parameter values. Co-design with AI experts must develop possibilities for practically achieving these functionalities in the bioadaptive controller.

5. Bioadaptive Systems

Bioadaptive systems show promise for personalized mobility restoration that outperforms the capabilities of even the best commercially available devices, characterized by a perfect engineering design. They combine components from multiple domains, each host to a sub-community that evolves its own culture and community awareness, but struggling severely with collaboration and synergy to leverage their collective capabilities [7]. Three distinct but critically interrelated domains can be identified. One domain includes novel neuromuscular interfaces (NMIs) for more natural, intuitive, and biologically-compatible control, such as the spinal cord, peripheral nerves, and muscles. An eclectic mix of modalities, designs, techniques, materials, and components is embraced here, resulting in a diversity of interfaces with distinctive benefits and drawbacks. NMI research is still in its early days, yet first-generation devices are commercially available and second-generation devices are in advanced clinical testing. However, poor access to comparative in-vivo efficacy and safety data drives up costs for early testers and end-users, discouraging investigation of more invasive NMIs that may provide enhanced benefit. The flexibility of such assessments in vivo and the rapid emergence of research-grade NMIs and clinical testing sites present an attractive opportunity to foster ecosystem development, allowing comparative studies and open-source sharing of experience and results beyond cohort-exclusive testing.

Bioadaptive systems require AI algorithms to decode intention from the outputs of the neuromuscular interface, as the latter don't output the actual intention of the user. Given the complexity of second-by-second evolution of commands in the users' muscle activation patterns, staircase learning approaches need to be supplemented by knowledge-based systems in addition to AI-based systems for design and testing. A natural avenue for achieving this is to exploit the everyday digital assistance being developed for application to smart prosthetic devices. In addition to enhancing usability in terms of matching speed and granting fine-tuning and recovery opportunities, this would open the mode of assisted deployment and training to diverse populations currently under-served in the realm of advanced prosthetics. The center of the universe, the human learned behavior, input this way is endlessly adaptable to improve skills for motor action tasks, model exploration, and real-world adaptation to age, stature, physical impairment, and skill level, in addition to being indefinitely storable. [14][15][16]

5.1. Concept of Bioadaptivity

In developing bioadaptive smart prosthetics, the prosthetics will detect the subject's muscle states and adapt their outputs. A method for adapting external prosthetic systems to physical impairments demonstrated an active monitoring-based scope adaptation on a prosthetic hand's output. Applications of bioadaptive prosthetics in body motion tracking and wearable systems have been developed inferring human intention using wearables like sensors, IMUs, and cameras to detect subjects' motions and controlling outputs of prosthetic devices or external devices, such as smartwatches and ceiling lights. But these bioadaptive interfaces do not directly handle physical conditions of the user affecting output performance coupling and modelling errors resulting in slow monitoring and discomfort or phantom motion occurrences during abnormal output generation. Therefore, the need for a method for properly quantifying severe interfacing issues is growing. Bioadaptive systems based on internal prosthetic signals have been developed and simulated. Some literature develops a model to quantify signal degradation in time-based domains and uses fuzzy rules-based systems to detect signal conditions. The scope of detection can be augmented using sophisticated classifiers. But they usually address muscle inactivity, noise, low movement whisper, and loss of channel issues and consider different stages of robustness without taking the physical condition of limbs or joint states into account or addressing network parsing. Therefore, the outputs of this signal-condition quantifying, accuracy-chance unpredictable, monitored systems are needed to be directly delivered to the controlling interface. The network parsing mechanisms of internal systems are still unrevealed, therefore, handled using weight parsing methods. However, parsing time is leveraging inaccurate when conditions evolve rapidly. To augment robustness, designed neural associative memories-inspired parsers a general adaptive combiner handles network parsing on tested setups.

5.2. Feedback Mechanisms in Bioadaptive Prosthetics

The inclusion of feedback mechanisms within bioadaptive prosthetic designs is examined with a focus on current interfaces that generate real-world parameters to control lower limb bioadaptive prostheses. This section further discusses the technological shortfalls, such as algorithms and hardware that generate stable feedback with custom bioadaptive stimuli. Numerous peripheral nerves commonly denoted as anterior and posterior nerves are considered in functional clusters or collections that can be used for bioadaptive interpretation while isolating external stimuli. Methods reviewed include intraneural recording methods that provide precise restoration of upper limb multi-dimensional control. These methods have yet to be explored more generally in the lower limb for leg designs capable of gait generation. Measurement feedback mechanisms for bioadaptive neural interfaces often arise from pressure, velocity, position, and temperature sensors. A class of neural interfaces that could send such feedback relevant to control limb motion are selected. The application of porous structures with regenerative electroactivity bridges the nanoscopic to microscale mechanotransduction gap. In addition to an advancing array of a biodegradable nanomaterial interface, their customization will afford the opportunity for treatment of osseointegration and bioadaptive software.

After losing a limb, patients face the reality that existing prostheses fall far short of their expectations. The shortcomings of clinically available myoelectric prostheses are exemplified by hand prostheses that only provide simple grasping or wrist rotation actions. These prosthetic movements are controlled by bulk contractions of the residual forearm musculature in a non-intuitive manner, that is difficult to master and frequently inconsistent. Patients with limb loss quickly learn to compensate without using their prosthesis. When asked, patients comment that their prostheses do not feel like a part of them, which may lead to device abandonment. Those using myoelectric prostheses cited both the lack of comfort and the lack of function as equal factors for abandonment [17]. Engineering advancements in signal processing and implantable systems have provided some improvement in the feedforward dexterity of devices, yet research participants are still not consistently fluent with their movements. 90% of upper limb peripheral nerve axons convey sensory information, which is not transmitted in any meaningful way by clinically available devices. As a result, there is increasingly active research into the integration of sensory feedback into prosthetic devices, with the specific goal of increasing patient embodiment of the devices by providing patients a greater sense of control and ownership of the prosthesis through more realistic sensory feedback, which improves fluency of movements.

5.3. Real-Time Adaptation to User Needs

Adaptive systems are an integral part of the developments towards bioadaptive smart prosthetics in the near future. Smart devices need to adapt in real-time to effectively integrate with the user and provide a direct method for them to perform their activities of daily living without extra conscious effort. In particular, during walking, a user needs to perform a multitude of different activities from simply walking flat, to stairs, ramps, or different surfaces. Furthermore, even during flat walking with the same speed, differences in metabolic costs in regards to gait strategies exist between individuals [8]. There are two strategies for adaptation of devices to user needs. First, these systems can automatically adjust their parameters, optimally guiding the user towards their goals by employing automated optimization. Automated tuning of both static and dynamic is demonstrated.

Controlling a device like a knee prosthesis with goal-dependent motion commands can actively exploit this inherent ability for adaptation by matching the intended movements to the effective motion of the residual limb. Here, the neuro-centred motor commands can either directly generate actuator outputs or adapt a tuning policy implemented as a dynamical system on a neuron-like computational unit to optimize target-output matching. Experiments that systematically vary the inertia of a driven limb note how participants increase their effort with greater imposed inertia, but introduce feedforward acceleration boosts that enable them to effectively match the actuator output to their intentions. During walking, varying tasks or user goals can lead to corresponding changes in foot position trajectories. These user goals introduce motion commands that may enter a closed-loop control structure akin to simplistic models of the central nervous system (CNS) that incorporate system dynamics and feedforward and feedback components.

6. Personalization of Prosthetics

Aligning neuroprostheses to the individual user’s needs and capabilities is key for potent mobility restoration, as each person exhibits different anatomical, physiological, and functional properties. Moreover, the user is central to the closed-loop neuroprosthetic control, which links their peripheral nervous system activity to external activity. Therefore, neuroprostheses should be personalized to the user as much as possible. User preference optimization of controllers should enable smooth control of the performed gait. Trained adaptive methods should allow user skill and symmetry balancing adaptation. In training, user motion and neurophysiological measurements should be modeled, and training phases should be determined. The frontline open-question is to better customize robotic rehabilitation procedure to the patient’s condition. This might include personalized neurorehabilitation protocols that take into account body-weight support, motivational input, and difficulty level. Another aspect concerns advanced indexes of gait training progression through body-loss control, non-gait posture supervision, real-time load estimation, and user’s intention prediction [8]. A preliminary adaptive methods that would provide fully automated optimization of controller parameters at the start of the rehabilitation are needed. Adaptive methods compensating, e.g. changing user mass are still undiscovered. Combinations of bioadaptive, predictive design research and machine learning-based control research are required to tackle the above questions. Types of compliance that take into account therapeutic stages, control transfer and patient performance are still absent.

6.1. User Profiles and Customization

Despite achieving recent advances in gait restoration for lacking lower limbs, the effectiveness of gait neuroprostheses relies on user-neuroprosthesis matching. Therefore, a multi-faceted approach is required to develop user specific gait neuroprosthetic solutions. Perspectives on potential approaches to enable user-neuroprosthetic matching, and their expected technological evolution are described.

Interfacing with the peripheral nervous system is an appealing method to address specific functional deficits. Through user-specific stimulation via surface, percutaneous, or implanted electrodes, the muscles can exert the majority of the work for its particular tasks. However, the accessibility of upper limbs or hands to control the interface might not be feasible for the patients of interest [8]. Coping with these device constraints, many patient-device interaction strategies have been presented in literature, leveraging the speed-accuracy trade-off of human control and most recent progress in activity recognition. User-device matching remains a challenging endeavor, as the same devices and interfaces require different control strategies for each new users. Designing such meeting of learning algorithms and neural devices, needs accessibility and within-the-loop optimization. Combined to learning approaches trained offline, these include auto-calibration, scheduling, and initial tuning algorithms that adapt the control on-the-fly to fit each user on their arrival to a new device.

Gait rehabilitation remains an open challenge for incomplete paraplegics due to spinal cord injury, a population with expected growth in age and lifespan. Focusing on user-inclusive and user-specific developments may broaden the coverage of solutions, address population needs, and empower the research community with practical realizations. This includes simplifying the neuroprosthesis to minimally invasive or surface electrode options and modularity and customizability for the hardware and the software. Incorporating these developments and conducting experiments to assess their clinical or usability asymptotic benefits is also suggested. Applying similar considerations on user-device matching and in-the-loop optimization may improve accessibility and initial user engagement for devices targeting upper limb and hand tasks or less common or challenging rehabilitation tasks such as brachial plexus repair, tongue, or vocal cord neuroprosthetics.

6.2. Adaptive Learning Algorithms

Optimizing robotic motions in bioadaptive smart prosthetics is key for real-time adaptation to these non-stationary and ever-changing environments. However, conventional model-based approaches for optimizing robotic motions are generally not suited here, due to the highly complex, nonlinear, and large-scale systems governing the environment and the robot dynamics. On the other hand, data-driven adaptable deep learning approaches (ADL) are fast converging to bioadaptive intelligence demands. However, these also have practical limitations, as common supervised methods are unable to learn during use. In contrast, continual learning approaches for ADL can learn from real-life data, enabling adaptive learning.

The challenge is that human-operated robots comprise now a days standard safety-critical, AI-based systems where human safety and controller safety are strictly decoupled in training and operation. Combining these seeks to design learning approaches maximally extensible to new knowledge and safe to human operation. A hybrid classifier-based method with output pruning and region filtering is detailed. A thorough evaluation of its performance against different intrinsic and extrinsic challenges is conducted. A systematic comparison with traditional pre-training process, as well as a user study with sample size, is also presented. Predictive safety nudge is demonstrated to provide sufficient time for safe shutdown without posing safety threat to the human operators on gyroscooters while learning simultaneously from low-risk experiences [18].

Mitigating prediction errors in bioadaptive smart prosthetics and exoskeletons is key for their effective adaptability to real-world environments. However, it remains unclear how to realize one-shot adaptation to new environments. To this end, a robot-environment predictive classifier (REPC) is introduced to enable the agent to recover from prediction errors through pre-emptive switching of locomotion modes immediately after the prediction of errors occurs. The effectiveness of the proposed adaptation method is verified through a case study of a legged robot. According to the simulation results, it is concluded that the proposed REPC-based method can realize one-shot adaptation to new environments that are completely different from those experienced during training.

6.3. User Experience and Satisfaction

The efficacy of novel neuromuscular interfaces, smart prosthetics, and bioadaptive applications will be assessed based on users’ experiences and satisfaction. The user acceptance of the proposed technologies and how they affect users’ everyday lives, perception of disability, and quality of life will be assessed in two ways: 1) a qualitative approach based on semi-structured interviews aimed at understanding how the technology affects mobility and accessibility in participants’ daily life and their perception of disability and satisfaction with the device and its use; 2) a quantitative approach based on standardized questionnaires. These questionnaires aim to assess user's satisfaction with the device with a disability-focused set of questionnaires on the perception of disability, mobility, acceptance and satisfaction with assistance devices. Midway through the project, an in-person qualitative exploration will be performed involving 36 people with upper- and/or lower-limb disabilities. Emotional and psychosocial areas will be assessed through open-ended questions. Interviews will last up to 90 minutes and will be recorded. Thematic analysis will be used to identify participants' needs, expectations, challenges, and suggestions. Twenty-four months post-deployment, user experiences will be re-evaluated via an online questionnaire. A multi-method approach will be used to derive quantitative data on the technology's usage, its effect on users' social and emotional quality of life, satisfaction, and acceptance. Inclusion and exclusion criteria will be defined with end-user representatives. People aged 18-90 years with upper- and/or lower-limb physical disabilities will be invited. Participants will be recruited through centres for people with disabilities and organisations representing caregivers or medics interested in assistive technologies. Eligible participants will be screened. Participants will be offered a modest compensation. Sample size estimates suggest the recruitment of a minimum of 80 participants over three years, with approximately 40-50 participants for the remotely administered online surveys. Data collection will be performed from September 2023 to February 2025.

7. Clinical Applications and Case Studies

Following on from the mechanical and neurorobotic research presented in the previous sections, this chapter presents application examples of recent innovations in brain-machine interface technology, bioadaptive control architectures, and neuroprosthesis design principles. Most of these systems are still in the early stages of research, where clinical-grade results were not yet achieved, but the presented cases illustrate the need to place human-users in the feedback-loop of robotics and bionics research. This chapter summarizes novel studies, publications, and ideas on the co-development of rehabilitation robots and personalizable bioadaptive devices with human-end-users. Individuals who undergo a limb amputation usually need to rely on the use of a prosthesis to re-establish mobility, independence, and well-being in their daily life and routines. The rehabilitation process to regain mobility following a limb loss is challenging, as it requires relearning walking using new motion patterns while adapting to numerous technological variables. Following amputation, individuals can ambulate using passive, mechanical devices or active, robotic prostheses. Despite demonstrating an increase in patient mobility, comfort, quality of life, and a reduction in co-morbidities over passive devices, active uses of bionic lower-limb prostheses with integrated robotics and neuromorphic technology are mostly limited to the research space, with commercial systems lacking the generativity of bionic devices that could allow individuals to adapt to changing environments. Research efforts to deploy neuromorphic neuroprostheses that can be personalized to both patient and limb have been limited. Neuromodulated bioadaptive devices can be derived from neuromorphic bioadaptive frameworks with a generative design assessment that begins with understanding the biomechanical needs of the patient in terms of range-functionality, linkage-kinematic design, actuation-motor characteristics, and feedback-sensing methods [19]. Customized components designed through finite element and rigid-body dynamics modeling and optimization are fabricated using selective laser sintering. These components are linked to form a lower-limb bioadaptive robot by off-the-shelf electronics that are wired to custom-designed electronic boards holding an application-specific integrated circuit host chip and other interface components. A neuromorphic controller is tested on the bioadaptive robot to assess voltage and frequency control of motion electroanatomically driven by surface stimulation of myelinated nerves. A personalized, bioadaptive neuromorphic neuroprosthesis is presented as a generative, sensorized, autonomous modification of the design platform. A wireless transcutaneous bus is tested to address device-wide interconnectivity using off-the-shelf components while enabling charge-balance metrics to assess stimulation. A flexible, soft bioadaptive element is presented that can be tailored to the output of the neuromorphic device to continuously modulate motion and perceive force during simultaneous stimulation. Finally, the bioadaptive element is integrated into a prototype knee, which is tested with a passive neuromorphic controller on this leg. Several biomechanical, sensory, and life-science algorithms are also included. The design, modeling, control, and evaluation of a neural interface for bone-anchored and soft-terminal robotics for prosthetics, orthotics, and neurorehabilitation are further examined [20].

7.1. Successful Implementations

An adaptive neuroprosthetic device that modifies stimulation based on perceived performance was tested in experiments with two post-stroke participants. A custom pushbutton joystick and feedback visual stimuli were used to manipulate device engagement. Participants could adapt their engagement behavior within a session. Measured muscle stimulation levels accurately reflected participants' effort and performance level. The findings demonstrate the feasibility of testing adaptive bio-engineering systems with participant-based performance feedback in closed-loop experiments [8].

A brain-computer interface (BCI) system that translates user intention to movement with both spiking and firing-rate neural activity is described. It is demonstrated that a deep learning matrix factorization method can learn a shared topological latent space from spiking activity, exploiting non-linear dynamics for high-dimensional representation, allowing separate decoders for each motor control task. The decoders' performance for closed-loop BCI control are tested on real data from a monkey control-ling a 22 DoF neurally-controlled robot arm.

The development of hybrid EEG-EMG movement intention decoders is addressed, focusing on traditionally considered physiological ways of measuring bra-in and muscle activity. It is demonstrated that the fusing of EEG and EMG data improves the robustness and precision of movement intention detection in tasks of physical activ-ities involving different limb motions and devices.

A design challenge of a bio-adaptive smart prosthesis proposed as a new approach for the development of personalized prosthetic systems and the strong interplay of the involved disciplines is reported. On this basis, the specific requirements of the adaptive interface layer for brain-machine intelligences for motion intent estimation in above-elbow amputees and the neuromechanical and signal processing based principles of the prosthesis motion control are introduced.

7.2. Patient Feedback and Outcomes

As part of the bioadaptive prosthetic systems developed within the project, new feedback and rehabilitation modalities were incorporated into the case studies. In this way, the PHA and patient therapists collaborated on defining a feedback protocol structured through Patient-Specific Information and Patient-Specific Adjustment/Rehabilitation. Feedback modalities were selected together with the patients and their therapists based. The list of techniques and tools below was therefore tailored to their unique rehabilitation journeys and conditions.

For Patient 1, an integrated multimodal sensory feedback was built for the GRP and OTA. For the GRP, aseptic vibrations and temperature estimation were bundled with tactile stimuli to produce sensations of grip force. A force sensor mounted to the prosthetic hand transduced these feelings in close-to-real time. By turning the intensity of the speed of vibration, the quantitative dimension of the perceived sensation was engineered for the discomfort boundary, slipperiness, and skin slippage. Real-time temperature estimation pertaining to the object touched was also mediated via a thermal sensory stimulation designed on top of a vibrotactile actuator along the palm. These virtual tactile cues were bundled into the prosthetic hand via a user-adapted and integrated inner structure. For the OTA, muscular approach and modal constitute flow sensation modalities were fully developed.

For Patient 2, the condition was complicated by other medical disabilities, all of which placed limits on available rehabilitation interventions. Collaborating care specialists and patient therapists were therefore consulted jointly in a co-design session to agree on the most crucial bioadaptive inputs and prosthetic responses suitable for Patient 2. For Patient 2, feedback protocols were significantly simplified in terms of both complexity and number of modalities and therefore shortened. It built on a minimal aural and vibrotactile feedback of the activity of pre- and post-motor commands. For the transradial prosthesis, a self-contained integrated device prototype was developed which was wearable and easy to fit for children, considering a wide range of ages and dimensions. It consisted first of a silicone layer that fit snugly and comfortably onto the forearm, personalizing the device size and parameters of the socket. The device also contained two augmented biomechanical designs spotting intensity and modulation via distal flexor side miniature actuator engagement. Feedback was delivered by two miniature and user-organized electronic components, a miniaturized vibrotactile actuator and a miniature piezo loudspeaker, one for each prosthetic side. Both the silicone device prototype and the externally mounted miniaturized devices were made waterproof, shielding electronics from any body fluid in the process. Their final designs were also tested for long-term integrated effects of intense motorized engagement.

7.3. Comparative Studies with Traditional Prosthetics

According to the literature addressing the evaluation of robotic and prosthetic devices, it deserves attention to spend time studying the feelability of an application. The prosthetic toe from the low limb is an actuation in a dexterous end-point removed from the human body. It undertakes required human movements instead of a human finger. The human prosthetic interaction layer improves human grasping by conveying information about the device contact as data received from the bioadaptive interface. The degree to which physical interaction is perceivable is defined human–prosthetic interaction [HPI] .

Once a patient is found suitable for a prosthetic device, the device is tailor-made according to the patient’s needs. In active intelligent prosthetic devices, at least three devices or components need to be present apart from the human-prosthetic interfacing layer: an end-to-end achievement component, actuated by a human–prosthetic interaction layer. The end-point component, foot or end-point must be mimetic to simulate the foot of a human end-effector, and is to be used for support and shock absorption during standing or walking. Throughout the use, the human computes a vector to translate a direction of interest into the desired angle (yaw). The human generates a vector or body displacement to make the desired action of each end-point component independently. However, this component cannot afford inferences about the intention of the received command. The acquired gait-based understanding module interprets the biodata received from the implant biosensors. Alternatively, interpretive data received from the HPE device can provide an abstract representation of the human motion in a successful grasping interaction. To follow the required human directives "hold" and "acknowledge," the device needs to sample the motion and calculate many parameters to know more details about the nature of the command before acting on it.

This body of work seeks on-beyond the wide range of design and application issues possessing prosthetic devices or devices of lower-level control. Other bioadaptive devices tend to be focused on the explicit understanding of human purposeful interaction with devices. A bioadaptive device is defined as a robotic device that acquires data of the human body and environment to use them to define and modulate its reaction. Analyzing the purposefulness at the devices’ interface provides insights into the understanding of a device to enable it in performing assisted movements. A bioadaptive prosthetic device needs actuators to undertake the provision of the commanded holding and its properties.

8. Future Directions

Recent Advances in Biomimetics for the Development of Bio-Inspired Prosthetic Limbs

Almost all arthropods have developed some sort of a biomechanical claw mechanism to assist in the task of gripping, although different species have developed different types of claws based on their particular skills set. Several studies are available in the literature on bio-inspired robotic hands inspired from such natural claws present in birds, insects and crustaceans. The claws of birds are primarily composed of keratinous material, which is relatively low cost and lightweight. In a recent work, an effort is made to mimic the design and actuation of the claw in birds and design a bio-inspired robotic gripper that can mimic the gripping functions of bird claws. Significant amount of tests are done for the new robotic gripper design including finger grip functionality tests and dry-grip tests for different sized objects. A working proto-type has been developed that is capable of flexible bidirectional rotary claw motion and a 3-fingered bioinspired pneumatic controlled bio mimetic articulated passive prosthetic spring loaded knee mechanism based on species such as birds, terrestrial mammals and reptiles is designed here as an alternative prosthetic who can live a healthy life without an amputated limb.

To begin with, significant anatomical differences between natural bionic matched articulated leg design and knee mechanism are discussed in detail. Not all the parameters governing the mechanical modeling can be modeled similarly as human due to drastically different biological construction. Nevertheless, to understand the basic working principles of such bionic leg, significant parallel reasoning technique is applied. Simulation takes into consideration planning structure motion parameters with initial angles and mechanism drive torque applied at joints. All designs are evaluated on Maximum stress and Von mises strain response under the application of 43.0 degrees torque for a 10kg weight object.

Adaptation Strategies for Personalized Gait Neuroprosthetics

Neuroprostheses, such as functional electrical stimulators, can potentially restore function through external activation of the central or peripheral nervous system and are therefore relevant in rehabilitation engineering. A paramount challenge is to restore mobility by effectively combining neuroprosthetic and wearable robotic approaches and to align neuroprostheses to the individual user's needs and capabilities. Apart from research on new devices, focus was given to other current limitations involving control and customization, including both the adaptation of the neuroprosthetics to the user’s musculoskeletal system and the adaptation of user commands to the devices’ specifications. Predictive simulations of the human-machine system in dynamic tasks appear to be a promising approach to customize design and control. Future work should focus on improving neuromechanical simulations of user-device interaction based on experimental data, following a multiscale approach. Important steps forward consist in devising efficient optimization approaches and quantifying uncertainties involved in the predictions. For user-device interaction optimization, the biomechanical model can be treated as a black-box mathematical function by estimating design sensitivities through simulation data and developing surrogate models.

During the last few years, the project has pivoted towards the general question of adding intelligence to assistive devices. Emphasis here regards the different possible levels of intelligence and the related control structures, ranging from executors, coordinators, and supervisors, to the organization of information to be handled. Such a classification naturally leads to questions of hierarchical or centralized vs decentralized structures and is relevant also for the combination of assistive devices, moved by diversified control strategies. Several case studies on cooperative multi-agent systems in robotics are ongoing. Additive Manufacturing technologies have now become established and supported by dedicated software tools for CAD modelling and simulation. Concepts such as bioinspiration, versatility, modularity, and reconfigurability still present significant research opportunities.

8.1. Emerging Technologies

The landscape of disability and mobility restoration has undergone revolutionary advancements. Classic technologies, such as traditional prosthetics and orthotics devices, have undergone steady development since their introduction. Innovations in biomaterials and power sources have improved the weightless and robustness of these classic devices, but they remain outside of the neurophysiological control loop. Currently, novel neural interfaces provide a biocompatible bridge that connects to the host peripheral nervous system (PNS). Next, developments in nano- and microtechnologies enable the design of smart, artificial limb devices that are bioadaptive or that return closed-loop sensory feedback to the host nervous system in a non-invasive or minimally-invasive way. Emerging technologies are anticipated to power a second turnaround in mobility restoration in the next decade.

Neuromuscular interfaces form a new generation of neural interfaces based on biocompatible technologies that provide increased signal resolution, a lower invasiveness than interfaces produced from macro-technologies, and that, in the closed-loop option, enable a bidirectional transfer of signals between the host and the prosthesis [7]. This integration has already proven capable of restoring dexterous control of bioinspired hand prosthetics in real-time through biocompatible and durable neural interfaces. Transferring this new paradigm to the lower limb is the greatest challenge for the realm of mobility restoration technologies to date. This transfer will require understanding about new concepts for the identification of the best available bioadaptive technologies for the lower limb, and required biomimetic mechanisms that expand the ambit of mobility restoration and supply a higher functional dexterity for a broader scope of daily activities. Designing flexible machinery with static and kinetic properties similar or complementary to its biological counterpart while simultaneously providing the requested on-board intelligence and smartness for its operation in the ever-changing environment will also require extensive R&D efforts.

Revolutionary on-board deep learning image analysis algorithms enable an increased bioadaptive capacity of artificial limb devices. Learning strategies, such as active learning and federated learning, can integrate new learning in a personalized manner for customized locomotion across contexts. On-focus extraction of hand detection position, a hidden Markov model (HMM)-based temporal transition framework for real-time class switching and Fischer kernel descriptor-based spatio-temporal features learning, can analyze a subject's motion intention in this homologous mine-biosynthetic finish. Bringing this deep-learning methodology to the prosthetic limb markets will require the semiconductor industry to expand the performance of biointegrated electronics from neurogram acquisition and analysis towards the decoding of perception or intention. [21][22][23]

8.2. Potential Research Areas

The advancement of bio-adaptive intelligent prostheses can substantially improve the quality of life for people with motor impairments. Towards this goal, we envision integrating advanced neuromuscular interfaces along with adaptive and intelligent strategies for personalizing the devices. It appears crucial to translate multi-phase estimators of the state of the user-device environment into bioadaptive control, which could result in prostheses that adjust their (inter)actions with the user. Moving towards more tight and symbiotic man-machine systems is an ambitious goal that requires specific expertise beyond the various fields covered in this special issue: most importantly, it calls for deeper cooperation and co-designing between the scientific, engineering, and clinical disciplines [8].

Research is needed to develop general concepts for the localization, interactivity, and rendering of surface EMG features. Deep-architectural models of bioinspired hierarchical feature abstraction should be contrasted for the extraction of generic and wear-agnostic device-agnostic features for users with a wide range of characteristics and contexts. Attention should be paid to researching neuro-technologies that complement learning and predictive capacities. Other robotics and psychophysics expertise would be required to design potentially disruptive and assessing man-machine interaction paradigms for studying generalization, portability, and adaptability. Potential form factor attributes also warrant further research since the representation and rendering of complex relationships between actions and effects makes interpreting them more difficult. Further studies are needed to investigate whether people with various impairments and non-expertise in the control of robotic devices intuitively understand and progressively adapt such approaches.

On the machine side, the integration of learning algorithms trained in simulations with control strategies for machines with simpler dynamics and reduced degrees of freedom remains immature. There is also a lack of direct, broad-spectrum human-device interaction benchmarks in critical performance facets that might unveil the capabilities, limits, and complementary roles of current learning-based approaches. The tools to analyze complex man-machine systems also need to be adapted.

8.3. Ethical Considerations in Prosthetic Development

The development of bioadaptive smart prosthetics powered by an adaptive interface of BCIs and neuromuscular interfaces brings forth several ethical considerations that need to be addressed in their development. The ethical considerations for prosthetic devices development necessitate the necessary stakeholders to clearly define the applicable safety and ethical guidelines for the adequacy of the devices. This necessitates a clear demarcation of the ethical and treatment parity principles for prosthetic devices as different devices on the spectrum of disability inclusion may fit into different regulation standards. Research and development of simple bioadaptive smart prosthetics will utilize the classical ethical principles of beneficence, non-maleficence, autonomy, and justice that should be addressed throughout the life cycle of the utensils [8].

Debates over ethical and safety matters for emerging technologies typically arise and gain traction too late as stakeholders race to harness technological potential. For this reason, the precautionary principle calls for the mass integration of ethical and safety considerations early on in innovation, development, and commercialization processes. In practice, this requires stakeholders, developers, the public, and policy makers to reach agreement on relevant issue boundaries —— particularly recently emerging scientific paradigms and technological families —— prior to their adoption. Current bioadaptive smart prosthetics developmental tools are novel varieties of brain-machine interface and neuromuscular interface systems to be co-implemented for the rehabilitation and restoration of full functionality in patients with neuromuscular disorder. This combination of technologies deserves particular scrutiny as special case in which science and technology emerge tightly interwoven, entirely untested, and in commensurable arenas on account of their dual engineering/emulation.

9. Conclusion

This paper reviewed the current scientific and clinical state of bioadaptive smart prosthetics, from signal origin and interface to control algorithm design and artificial intelligence. The different types of signals that could be used as control interfaces were explained, ranging from muscle signals to brain signals, and various types of sensors and their combinations were highlighted. On the implementation side, the comprehensive design process of biomechatronic limbs was detailed, from establishing multimodal models to evaluating performance in different metrics. AI was discussed extensively from both the engineering and ethics sides, with deeper considerations of explainability and distrust-related bias.

Research and development on bioadaptive smart prosthetics are at the intersection of different scientific and engineering disciplines, involving biomechanics, robotics, control theory, circuit design, sensor and material science, artificial intelligence, human-centered design, ethics and regulation, and implosive consideration. Among the large pool of talented researchers over the globe, efforts need to be better organized to reduce redundancy and build a collaborative ecosystem in order to expedite the translation from benchtop to rehabilitation. Among all segments of bioadaptive smart prosthetics, the restoration of mobility in above-knee amputees, powered lower limb prosthesis and artificial limbs, remains the biggest challenge and the highest need. The overall development flow of bioadaptive powered lower limb prosthesis was summarized with an emphasis on control accounting for mode and gait variability. The central theme of the flow is modeling the user, the prosthesis and the environment in a joint biomechatronics approach followed by the synthesis of a bioadaptive control that is evaluated in simulation and subsequently on real limb-user systems. With the hope of bettering the mobility of individuals with disability whether it's neuromuscular or artificial in nature, further research needs to be conducted from modeling multi-scaled human control systems to bioadaptive control in direct mapping and two-neural-layers.

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