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Transferrable Expertise From Bionic Arms to Robotic Exoskeletons: Perspectives for Stroke and Duchenne Muscular Dystrophy

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***Abstract*—Upper extremity function is affected by a variety of neurological conditions. Robotic exoskeletons offer a potential solution for motor restoration. However, their systematic adoption is limited by challenges relative to human intention detection and device control. This position article offers a focused perspective on this topic. That is, on how knowledge gained from the design and implementation of human–machine interfaces (HMIs) for bionic arms can benefit the field of rehabilitation exoskeletons. Three broadly used HMIs in bionic arms are here investigated, including surface electromyography, impedance, and body-powered control. We propose that combinations of these HMIs could push forward upper extremity exoskeleton development. In this context, we provide concrete applicative examples in two selected clinical scenarios, including post-stroke and Duchenne muscular dystrophy individuals. The discussed solutions can open new avenues for the translation of robotic exoskeletons in a large set of clinical settings and enable a class of exoskeleton technologies that could support a broader range of impairment and disease types.**

***Index Terms*—Bionic arms, Duchenne muscular dystrophy, robotic exoskeletons, stroke, upper limb.**

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I. Introduction

THE ABILITY to perform coordinated arm-hand movements relates to the quality of life, as well as to social participation and acceptance [1]. As we manipulate objects primarily through our hands, neurological injuries and disorders affecting the upper extremity [1] highly impair one's ability to interact with the external world. In this context, robotic exoskeletons have been long developed for restoring impaired motor functions [2], [3], due to their potential in promoting active user participation [4], independence [5] and potential suitability for home rehabilitation [6].

The research field of robotic exoskeletons has been growing rapidly [2], [3], [7], resulting in an explosion of wearable assistive and rehabilitation technologies [8]. However, demonstrated functional and clinical impact is still limited. Kinematic compatibility and the additional weight imposed on the existing limb by a robotic exoskeleton are important factors limiting robotic exoskeleton use. The development of soft exosuits, aims to easier fitting and lightweight designs that require less energy to use [9], [10]. Additionally, the lack of a rigid frame simplifies sensor placement, and prevents extra strains to the body of the user. However, soft exosuits result in a limited amount of support compared to rigid robotic exoskeletons [9]. Bos *et al.* [3] identified forty-six hand exoskeletons intended for use as daily assistive devices, yet most of them did not reach the market. Moreover, Maciejasz *et al.* [7] concluded that the results of the clinical evaluation of robotic exoskeleton-aided therapy are sparse. Additionally, despite the large research performed in the last 30 years [11], the effectiveness of robotic therapy over conventional physiotherapy is modest [7], [12], especially in people with neuromuscular injuries (e.g., stroke) or progressive impaired function (e.g., Duchenne Muscular Dystrophy or DMD). Important causes are the slow translation of robotic exoskeletons from laboratories to clinical setting, where clinical trials can further assess their efficacy [7], and the fact that the broad use of exoskeletons for daily or home use has not been consistently translated from the laboratory to the clinic [13]–[15]. Additionally, the lack of natural and intuitive human-machine interfaces (HMI), presents an important challenge for the future, indicating that the use of robotic exoskeletons in the real world requires significant improvements before it can be realised [5], [16].

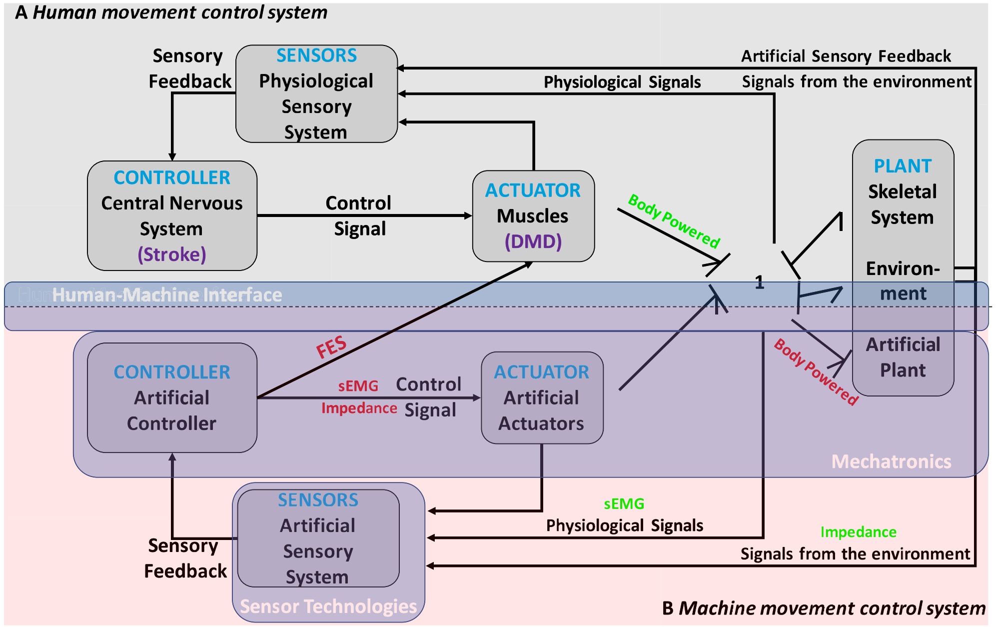

Fig. 1. This figure illustrates A) the human movement control system together with B) the machine movement control system. The machine movement control system can be a robotic exoskeleton or a bionic limb. With purple are noted the two clinical cases discussed in this article. DMD affects the muscles, and stroke causes central nervous system disorders. With red and green we can see the interaction between each of the three human-machine-interfaces discussed and the human, plus functional electrical stimulation (FES). The input signal (motor intention detection) and the resulting interaction are noted in green and red, respectively. The three major components of bionic limbs and robotic exoskeleton systems are highlighted in the machine movement control system. The mechatronics consist of the controller, actuator and the device (bionic limb or robotic exoskeleton), the sensor technologies refer to the artificial sensory system and the human-machine interface represents the flow of information between the human movement control system and the machine movement control system. Modified from [42].

On the other hand, the field of bionic arms has undergone substantial scientific and technological advances with direct clinical and market impact [17]. Prosthetic procedures, such as targeted muscle re-innervation (TMR) [18] and osseointegration, greatly improved surface electromyography (sEMG)-based decoding and device control [19] as well as donning/doffing [20] and stability of the bionic arms fixation. Such procedures have opened up new opportunities for HMI. In the case of people with brachial plexus injury, where a robotic exoskeleton would be the preferable (minimally invasive) technology, elective amputation and use of a bionic arm is sometimes preferred [21]. In this way, people with critical injuries can substitute a non-functional limb with a highly functional bionic limb, indicating that bionic technology is more mature to enhance functional recovery.

Robotic exoskeletons such as the MyoPro elbow/wrist/hand orthosis [22], [23] and the SaeboGlove [24] are commercially available. However, in terms of HMIs, they are less advanced compared to commercial bionic limbs, which are driven by pattern recognition myocontrollers [25], [26] or biomechanical models [27], enabling multiple degrees-of-freedom (DOF).

Given the close relation and overlap between bionic arms' and robotic exoskeletons' HMIs (see Section II), this article proposes a focused perspective for how expertise and technological advancements in bionic arms could be translated to the developing field of arm-hand exoskeletons. We trust that the development of such a roadmap will lead to a new class of wearable robots that can seamlessly cooperate as a natural extension of the human body.

In this article, we first introduce three key technologies well established in current HMIs for bionic arms including sEMG, impedance and body-powered control. Second, we propose how HMIs can be translated to exoskeletons. Third, we introduce relevant clinical scenarios that can benefit from the use of exoskeletons, including stroke and DMD. These key scenarios allow distinguishing between exoskeletons used for rehabilitation or restoration (i.e., stroke scenario) and those used for functional replacement, i.e., assistive technologies for daily use (i.e., DMD scenario). Finally, we discuss how these technologies can be combined in order to be used for the presented clinical scenarios. This provides new perspectives on how exoskeletons can be interfaced to individuals with neuromuscular impairments.

II. Focused Perspective

A. Learning From Bionic Arms

Research on prosthetic arms goes back for centuries [28], reaching a strong impact on the market [29]. Arm exoskeletons share a similar design and functional features to current bionic arms, yet underline unique and distinctive attributes, i.e., exoskeletons act in parallel to the impaired limb, rather than replacing it. Fig. 1 shows differences at the HMI level across bionic arms and exoskeleton technologies. The human movement control system (Fig. 1, A) and the machine movement control system (Fig. 1, B) act in parallel to each other for exoskeletons but in series for bionic arms. In this context, we argue that the transfer from bionic arms to exoskeletons should focus on the HMI level.

The term HMI refers to methodologies for the identification of the user's intent to move from biological signals (i.e., surface electromyograms or sEMG) or body force and position data and its translation into robotic commands. Numerous invasive [30], [31] and non-invasive [32]–[37] interfaces were developed in the past and applied to both bionic arms [30]–[34], [36], [37] and exoskeletons [35], [38]–[41].

There are different levels of interfacing with the human [42] (Fig. 1). Myocontrolled bionic arms [32], [33] interface with residual muscle tissues replacing the missing limb. There are also bionic lower limbs that interface with the musculoskeletal plant via impedance control [34], [35] (utilising the interaction between the user and the robotic limb) or via body-powered control [36], [37] (by using an intact limb to mechanically control a bionic limb). Neuroprostheses are available to stimulate muscles or nerves [30], [31] to elicit movement in the impaired limb.

B. Clinical Scenarios

In this position article, we rely on two representative key clinical scenarios including stroke [43] and DMD [44]. For both scenarios there is a clear need for active support and robotic exoskeletons present a feasible solution. However, despite this similarity both conditions present clear differences at the HMI level. Stroke represents a class of conditions where the affected individual needs to re-learn how to use their limbs, thus requiring HMIs providing minimal assistance in order to facilitate motor learning. On the other hand, muscular dystrophies are characterized by a progressive loss of muscle strength, with no potential for motor function restoration, thus requiring HMIs providing maximal assistance to postpone tissue degeneration. By discussing extensively those distinct neuromuscular deficiencies we cover a large HMI spectrum which, if addressed properly, would enable a class of exoskeleton technologies that could support a broader range of impairments and disease types.

Stroke: It is caused by a lesion in the central nervous system or CNS and results in loss of motor capacity [43]. According to a recent study by the world stroke organization, it has an incidence of 35-909 per 100,000 people per year worldwide [45] and the observed acceleration in the ageing population is expected to raise these numbers [45]. Stroke results in motor impairment with a level of similarity to other neurological conditions including multiple sclerosis (MS) [46] and spinal cord injury (SCI) [47], i.e., early fatigue onsets, spasticity, paresis, muscle contractures and rigidity, reduced mobility and musculoskeletal coordination and mechanical tissue changes [48]. Hence, exoskeleton technologies effectively supporting stroke rehabilitation could have a broader impact on other clinical scenarios, i.e., SCI and MS.

Exoskeletons targeting stroke individuals are designed for rehabilitation of the impaired motor function [8]. Currently, static splints are used for increasing range of motion and preventing contractures [49]. However, although highly prescribed by doctors, these are reportedly ineffective [50] and uncomfortable for long-term use [51]. Active exoskeletons are also broadly for clinical or home rehabilitation [3].

For stroke patients, exoskeletons are controlled via assistance-as-needed strategies to enable the active participation of individuals during the rehabilitation process [52], [53].

DMD: It is an X chromosome-linked progressive neuromuscular disease which leads to physical disability and shortened life expectancy [54]. There is currently no therapy developed for DMD. Nevertheless, recent technological advances have significantly increased the life expectancy of people with DMD [55]. Due to this fact, the population of individuals with DMD is expected to significantly increase in the near future [56]. DMD presents a representative case for other existing muscular dystrophies as it is the most common and severe form of muscular dystrophy [57], with an incidence of 1 out of 4,000 male births [58].

People with DMD need exoskeletons to maintain tissue integrity. This can be achieved by the decrease of detrimental mechanical load on their muscle tissues in order to minimise contractures and joint deformities that develop due to disuse of the limb [59]. There is evidence that people with DMD can greatly benefit from the use of arm exoskeletons [60], thereby promoting the use of the upper limb. Even more importantly, DMD individuals need devices to assist function in daily living for a prolonged period of time [61]. Regarding the hand, the only exoskeletons systematically adopted in people with DMD are passive splints [62]. These aim at maintaining a large active range-of-motion for the fingers and the wrist and slow the development of contractures.

Muscular dystrophies present a different scenario than stroke as the disease is progressive. While short-term therapeutic benefits may be seen with the use of a device, the primary focus is on providing as much assistance as possible. Thus, the exoskeleton should minimise the effort of the user to enable activities of daily living.

C. Key Technologies in Human-Machine Systems

Whether for exoskeletons or bionic arms, an HMI should enable the robust identification of the user's movement intent and translate it into machine commands. In the remainder of this section, we introduce three HMI technologies as well as the use of functional electrical stimulation (FES), which we selected for their potentials. These selected technologies will be combined together in Section III to compose HMIs specifically tailored for stroke and DMD.

sEMG Control: Myocontrol is broadly used in bionic arms [63], [64]. Direct sEMG control [65] is typically combined with co-contraction to enable switching across DOF. However, it has been reported as an unintuitive approach providing limited gains in functionality [64]. More advanced approaches rely on two main techniques [66]. The first is model-free machine learning [67]. The second emerging one is the model-based approach using musculoskeletal modelling [68]–[71]. Machine learning uses multi-channel sEMG recordings in conjunction with model-free algorithms in order to achieve higher functionality and control over more DOF. In this context, pattern recognition [72] (classifying a finite number of movements based on features of the sEMG signals) and regression [73] (continuous mapping of sEMG signals to kinematic variables) are currently used for the control of bionic arms. However, training in a specific spatiotemporal condition using machine learning does not necessarily translate into another [74]. The combination of such approaches with biomechanical models can overcome this limitation [68], as recently demonstrated [69], [70].

Pros and Cons: The benefit of myocontrol techniques is that they allow for the user's intent to be detected before the movement actually takes place and even if no mechanical movement is possible [68]. This way, it is possible to synchronise the actual muscle contraction to the movement of a device, thus making the combined movement more intuitive [64]. On the other hand, sEMG can be contaminated by electromagnetic interference, skin perspiration and fatigue [75], and movement and crosstalk artefacts [76]. The use of sophisticated machine learning techniques is reportedly low for more challenging 'outside the lab' conditions [64] as it requires significant set-up and training time. Also, myoelectric bionic arms tend to be rejected by the user due to unpredictability in their response [77].

Impedance Control: Impedance and admittance control govern the relationship between position and force (torque) rather than controlling either position or force explicitly, where admittance is the inverse of impedance. The impedance control approach was originally proposed by Hogan [78] and has had widespread success in wearable robotic technologies for the lower extremity. For example, Herr *et al.* have used impedance control to govern the behaviour of their bionic ankle and knee, which have had promising clinical results [76], [77]. Furthermore, Goldfarb *et al.* have implemented impedance control in their robotic leg, which has provided a rich foundation of work on the development of many aspects of robotic legs [81], [82]. Impedance control is particularly useful for lower extremity bionic limbs because it permits mechanical dynamics between the body centre of mass and the ground, governed by the multi-joint mechanical impedance of the robotic hardware. Thus, impedance control circumvents the use of high-gain position-controlled mechanisms, which would cause the wearer to 'ride' the robotic leg or exoskeleton. This approach contrasts the control of upper limb robotics; bionic arms have traditionally used muscle sEMG as a command signal, which often controls the velocity of the joint or grasp mode [33], [83], [84].

Pros and Cons: One unique characteristic of impedance-based control schemes is that they enable mimicking the compliance of the musculoskeletal system. Knowledge of how impedance is regulated during movement forms the foundation of a biomimetic impedance control approach, which can be implemented in the control of exoskeletons and bionic arms. The impedance control framework is the only control strategy that permits the ability to match human regulation of kinetics, kinematics, and impedance, simultaneously. However, further studies are needed to ascertain the value of the biomimetic impedance framework, both in bionic limbs and exoskeletons. This case is dominated by lower extremity bionic limbs. Upper extremity bionic limbs are stiff mechanisms controlled using sEMG thresholding or pattern recognition. The work from Keemink *et al.* [85], recently addressed the cons of admittance control and provided a comprehensive and complete admittance controller framework, that can be used for physical human-robot interaction and enhance user tailored control.

Body-Powered Control: To control a bionic arm, it is important that the user can provide a proper feedforward signal. Equally important is that the user receives a proper feedback signal. This was already pointed out by Wiener in 1948 [86]. The human hand has excellent control; there is a wealth of effectors and of afferent information (muscle spindles and Golgi-tendon organs) providing excellent (proprioceptive) feedback. In body powered bionic arms, shoulder movements are most commonly harnessed to provide the intent of the motion. The shoulder muscles involved provide proprioceptive feedback. The bionic arm user can learn how the position of the shoulder and/or the upper arm at the unaffected side is a measure for the opening width of the bionic arm. Equally, the user can learn to interpret the forces perceived on the shoulder as a measure for the applied pinch force of the bionic arm.

Existing control methods include harnessing body movements, cineplasty [87], muscle bulging [88], myo-electricity, and myo-acoustics [89]. New control methods explored include peripheral nerve interfaces [90] and brain-computer interfaces [91].

Pros and Cons: Given the need for feedback, only harnessing body movements, cineplasty, and peripheral nerve interfaces are feasible control methods. Research in body-powered bionic arms focusses on lowering the operating forces to enhance force and displacement perception For all options, the design of a servo mechanism is instrumental [92]. All that is said for bionic arms applies to robotic exoskeletons as well – it is all about how a human being can control a machine. Closed-loop control is also a necessity here. However, body powered prosthesis, are quite limited in the number of DOFs that they can restore and actively control.

Functional Electrical Stimulation (FES): FES is broadly used together with robotic exoskeletons [93]–[96]. Transcutaneous FES is integrated with exoskeletal structures in which the exoskeleton takes a double function: i) it carries the electrodes; ii) it stiffens or stabilises the joints that cannot be well controlled by FES alone. A typical example of such a transcutaneous FES upper extremity exoskeleton is the Bioness Inc. H200, a device that has been used in clinical applications for almost two decades. Current challenges for the seamless integration of all these technologies into an intelligent exoskeleton for unassisted hand grasp are mainly on the material side on stretchable electronics, the electrode-skin interface, and personalisation.

Pros and Cons: For the upper limb, recent reviews concluded that FES is a promising technology for rehabilitation in combination with robotic exoskeletons [97] and that FES systems reduce spasticity and improve the range of motion and the quality of life of people with stroke [98]. To the authors' best knowledge, there is no evidence of FES being used with individuals with DMD to assist in functional movements of the upper limb. However, there are studies [99]–[101] on the therapeutic effects of FES for people with muscular dystrophies, but with controversial and sometimes contradicting results. It is therefore important to approach this idea with the appropriate caution since it is known from the literature that exercises imposing high mechanical stress and

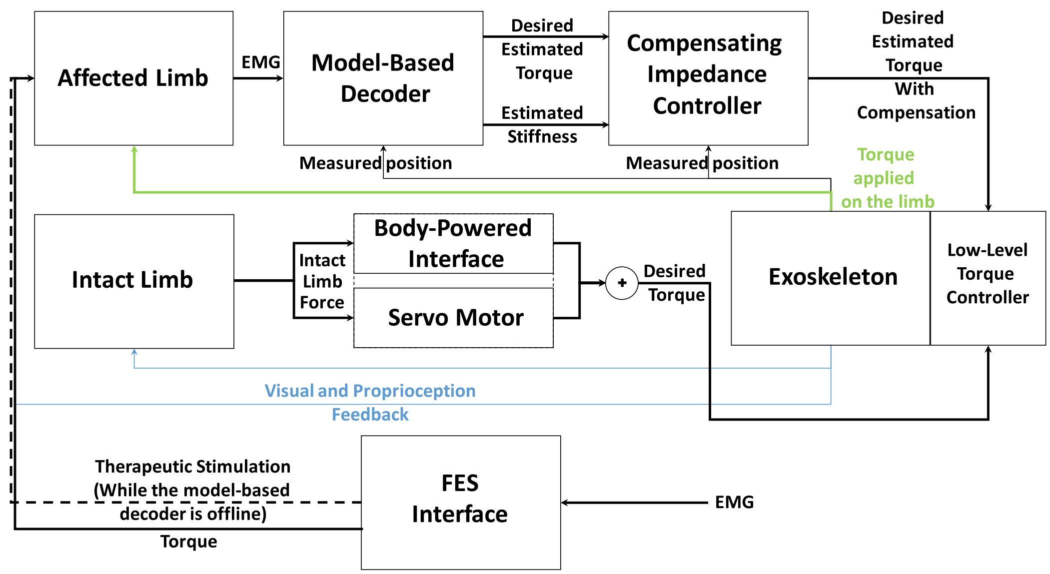

Fig. 2. This figure illustrates the proposed control diagram for stroke, including a body powered interface together with sEMG and impedance. All the separate elements are described in detail in Section III.

eccentric muscle contractions can be harmful to individuals with DMD [102].

III. The Proposed Position

In the previous sections, we described three key HMI components currently used in bionic arms (sEMGs, impedance control and body-power schemes) and neuro-prostheses (FES). Here, we discuss our position regarding their combined use and translation into robotic exoskeletons as an intervention for the clinical scenarios discussed previously.

Position for Stroke Case-Scenario: Fig. 2 shows the conceptual design of a stroke-specific HMI scheme. The user intent is estimated by means of sEMG from the affected limb [32], [33]. In stroke patients with residual proprioception [103], this provides a level of closed-loop control. The sEMG signals are directed together with position information from the robotics exoskeleton to a model-based decoder [19], which provides an estimate of the desired torque in the limb's joints. This allows the implementation of control strategies in which the subject is supported as little as needed and proportionally to residual force, central for neuroplasticity [64]. Moreover, this allows the estimation of joint stiffness, as previously shown, and therefore establishes closed-loop controllers operating in the impedance/admittance domain [104]. An impedance compensation controller receives the estimated torque and stiffness from the model and also position information from the exoskeleton. In this way, it can be directly controlled from the sEMG-decoded stiffness and compensate for altered joint mechanics due to tissue structural changes [48], [104]. This can be achieved by a position-based compensator. The impedance compensation controller needs to be calibrated beforehand in order to compensate for joint-stiffness induced torques, similar to the active stiffness compensation proposed by Lobo-Prat *et al.* [105]. Additionally, the impedance compensation controller can be used to provide active gravity compensation including weight compensation of handheld objects [105], or manipulate the virtual dynamics of the device and add an extra level of control customization [106]. The final desired estimated torque is directed to a low-level torque controller and the outcome torque is applied to the limb by the exoskeleton. For individuals with hemiparesis, body-power technology can be used to harness the functionality of the non-impaired side and further enhance the active participation of the user. In the case of more impaired subjects, the torque provided by the non-impaired limb can be amplified by the addition of a servo motor (Fig. 2). In this case, the desired torque is also directed to a low-level torque controller and the outcome torque is applied to the limb by the exoskeleton. We propose the use of electrical stimulation (ES) as a means to improve upper limb functionality by reducing muscle contractures and spasticity while improving coordination [107]. This is also reported to happen in cases of MS [108] and SCI [109], however for the lower limb. With such use of FES, we can optimise the use of the robotic exoskeleton by the human.

Position for DMD Case-Scenario: Fig. 3 shows the DMD specific HMI scheme. Similar to what we proposed previously for stroke, the user and the robotic exoskeleton interface by the means of sEMG of the affected limb. Closed-loops sEMG control is achievable in DMD with residual proprioception [110]. We propose to combine sEMG with a virtual impedance/admittance model similar to [106], [111]. sEMG signals are directed together with position information from the robotic exoskeleton to a time-varying model-based decoder [19], which estimates the desired torque in the limb's joints. The model-based decoder adapts with time (time-varying) to the progress of the disease. This can be done via multi-scale mechanobiology models characterising cellular-to-organ scale musculoskeletal adaptations [112], [113]. The impedance compensation controller will receive the estimated torque and stiffness from

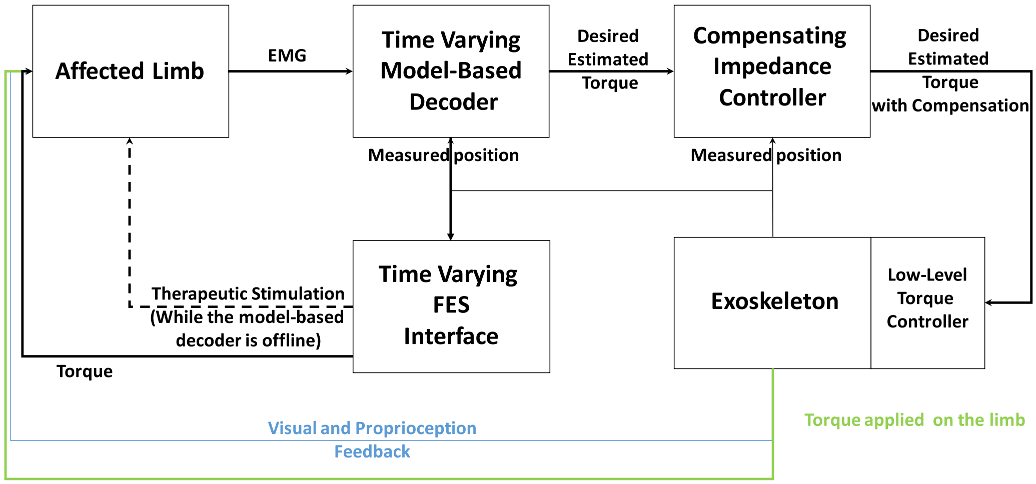

Fig. 3. This figure illustrates the proposed control diagram for DMD. In this case, we combine sEMG with a time-varying biomechanical model (due to the progressive nature of the disease) and impedance control. All the separate elements are described in detail in Section III.

the model and also position information from the exoskeleton. This can be achieved by a position-based compensation similar to the one applied to abnormal joint stiffness induced forces by Lobo-Prat *et al.* [106]. The impedance compensation controller needs to be calibrated beforehand in order to compensate for such parasitic forces and torques, due to abnormal joint stiffness [106]. Additionally, the impedance compensation controller can be used to provide active gravity compensation [105] or manipulate the virtual dynamics of the device in order to add an extra level of control customization for the user [106]. The torque estimated by the model-based sEMG decoder is algebraically added to the torque estimated from the compensatory impedance controller and will be sent to the low-level torque controller. The outcome torque will be applied by the exoskeleton to the affected limb.

The therapeutic ES will act when the sEMG-impedance hybrid is offline. The interaction between the sEMG model-based decoder and the ES module will have a dual nature. First, it tells the ES module how much exercise is needed based on the quality of the sEMG measurements. Second, it will indirectly affect the performance of the model-based decoder by improving muscle quality. The ES module can be integrated into the robotic exoskeleton to enhance portability.

IV. Discussion

This position article presents two HMI designs for addressing distinctive clinical scenarios including stroke and DMD. For both scenarios, the proposed designs include different combinations of sEMG, impedance control, and body-powered technology in combination with FES. The technologies discussed in this article covered three crucial objectives for the control of bionic limbs: 1) the connection to the human body (sEMG) 2) the control of actuators (impedance/admittance) and 3) usage of the residual limb capabilities (body-powered). In this context, FES enables establishing neuroprostheses for upper extremity function restoration as a stand-alone [107] or in combination with a robotic exoskeleton [114]. Therefore, FES is the optimal starting point for investigating new concepts of integration between bionic prosthetics and robotic exoskeleton technologies. The HMI type considered in our position article aims to operate at a lower level than cognitive HMIs. Our proposed HMIs aim to interface wearable robots with the human neuromuscular system via the recording and processing of bio-electrical information.

Additional HMI technologies exist that were not covered by this article [42], [115]. Common non-invasive HMIs include brain-computer interfaces like electroencephalography [116] (EEG), and near-infrared spectroscopy [117]. At the muscle level, interfaces like mechanomyography [89] and sonomyography [118] aim at providing alternatives to sEMG. Last but not least, HMI such as eye tracking, tongue interfaces and joysticks have been heavily used for the control of bionics [42]. Those have a clear disadvantage of sacrificing one function to support another.

In addition to HMI, there are a number of issues already addressed in bionic arms, which can enhance the adoption of exoskeleton technologies. Effortless donning and doffing of an external device can have a positive effect on a user's satisfaction and presents an aspect already well-studied for bionic arms. Moreover, cosmetic gloves and artificial skin ensure a natural appearance and thus enhance the acceptability of such devices. Exoskeletons can benefit from the successful examples already set for bionic arms. The fact that amputees may have specific surgeries performed to improve fit (like osseointegration) or bionic arm control (like TMR) suggests that surgical procedures could become available for individuals using exoskeletons. Such procedures could also restore sensory feedback in people with Stroke or DMD, when impaired, similar to what is done for amputees [119]. This is important for the upper limb, as the sense of touch and proprioception is central for object manipulation [120]. Additionally, the restoration of sensory feedback enables natural closed-loop control (Section III) and improves fine motor control in terms of coordination and dexterity [121]–[123]. However, it is important to consider that while amputees might have the level of commitment to consider invasive surgery, paretic patients or muscular dystrophy patients may not have it. In these neurological conditions, it is not uncommon that sensory feedback and proprioception may be restored through non-invasive ways, such as rehabilitation [124] or that are not even impaired [103], [125].

V. Conclusion

A focused perspective on the development of personalised HMI schemes to enhance upper extremity function via robotic exoskeletons, is discussed for the cases of stroke and DMD. We believe that the use of the proposed schemes can help the development of better HMI schemes for users of robotic exoskeletons of the upper limb, enhance function and daily use of such devices, and inspire more research towards the development of hybrid HMI.

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