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How the CYBATHLON Competition Has Advanced Assistive Technologies

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Abstract

Approximately 1.1. billion people worldwide live with some form of disability, and assistive technology has the potential to increase their overall quality of life. However, the end users' perspective and needs are often not sufficiently considered during the development of this technology, leading to frustration and nonuse of existing devices. Since its first competition in 2016, CYBATHLON has aimed to drive innovation in the field of assistive technology by motivating teams to involve end users more actively in the development process and to tailor novel devices to their actual daily-life needs. Competition tasks therefore represent unsolved daily-life challenges for people with disabilities and serve the purpose of benchmarking the latest developments from research laboratories and companies from around the world. This review describes each of the competition disciplines, their contributions to assistive technology, and remaining challenges in the user-centered development of this technology.

1. INTRODUCTION

An estimated 15% of the world's population live with some form of disability (1). Assistive technology can play a key role in improving the quality of life of individuals with physical disabilities by enabling independence, better inclusion, and participation in society (2). However, a paucity of user involvement during the development of assistive technologies often leads to devices that do not fully meet the actual needs of people with disabilities, which in turn leads to frustration and increased device abandonment (1, 2) by end users. A better understanding of the everyday challenges experienced by people with disabilities as well as the active inclusion of user expectations in the development process would probably lead to more functional and satisfying devices.

Based on these observations and assumptions, CYBATHLON was founded at ETH Zurich in 2013. CYBATHLON aims at driving user-centered development of assistive technologies for people with disabilities by providing a benchmarking platform in an out-of-laboratory setting (3, 4). As such, CYBATHLON organizes international competitions in which people with disabilities (called pilots) compete against each other with the help of their assistive technology in tasks representing their actual daily-life challenges. The pilots are part of teams that include a technology developer (usually a company or a research laboratory) and, optionally, additional subject-matter experts such as clinical staff, therapists, or orthotics and prosthetics professionals. CYBATHLON further provides a platform for exchange about the opportunities, challenges, and needs of assistive technology among its participants. The competition consists of six individual disciplines (**Figure 1**): the Brain–Computer Interface Race (BCI Race), the Functional Electrical Stimulation Bike Race (FES Race), the Arm Prosthesis Race (ARM Race), the Leg Prosthesis Race (LEG Race), the Exoskeleton Race (EXO Race), and the Wheelchair Race (WHL Race).

In each discipline, the pilots are challenged to perform multiple tasks, each of which is designed to address a specific unsolved daily-life challenge, enabling evaluations of current limitations and helping to accelerate the technological development of innovative solutions. Tasks are developed in close collaboration with an interdisciplinary group of experts, consisting of end users, researchers, clinical specialists, and orthotics and prosthetics professionals. The design of the tasks evolves over time, from one competition to the next, in order to gradually increase the difficulty of existing challenges and to introduce novel challenges to the participants once they have proven

Figure 1

Overview of the six disciplines of the CYBATHLON competitions held from 2016 to 2020: (*a*) the Brain–Computer Interface Race, (*b*) the Functional Electrical Stimulation Bike Race, (*c*) the Arm Prosthesis Race, (*d*) the Leg Prosthesis Race, (*e*) the Exoskeleton Race, and (*f*) the Wheelchair Race. Each discipline has a distinct set of eligibility criteria for both the pilot and the assistive device. The competition tasks in each discipline represent challenges of daily life of people with disabilities. Photos provided by CYBATHLON/ETH Zurich.

their ability to complete the previous tasks successfully. Each task is specified to a high degree in the rule book (e.g., 5) such that the required device functionalities, the rules for performing a task, time limits, object dimensions, positions, and orientation are known to the participants beforehand. The rule book is published several years before a competition to ensure that the participating teams can go through the necessary technology innovation cycles and prepare for the competition.

To encourage the teams to develop novel and innovative technological approaches, the organizer defines as few medical and technology eligibility criteria as possible in the rule book. The criteria serve to (*a*) guarantee a level playing field among the participants and (*b*) ensure that participation is safe for the pilot from a medical and technical perspective. Teams can apply existing, adapted, or completely novel approaches or technologies (prototypes) (3). A detailed description of the medical and technology eligibility criteria is included in the 2021–2024 rule book (5).

Multiple CYBATHLON competitions have now been held. From 2016 to 2020, more than 120 teams from more than 30 countries have participated (for more detailed information about the events and participating teams, see **Table 1**).

The aim of the present review is to provide insights into how CYBATHLON has driven the field of assistive technology since its inception and to outline its impact on this field of research. Each of the six following sections crystallizes the advancements and remaining gaps in one of the CYBATHLON disciplines.

2. THE BRAIN–COMPUTER INTERFACE RACE

2.1. Background

The use of brain–computer interfaces (BCIs) is a cutting-edge approach that aims to enable some independence for people suffering from severe motor disabilities (6–8). In the context of

Table 1 Overview of the main CYBATHLON competitions held since 2016

Event	Date	Location	Discipline(s)	Number of participating teams	Number of participating countries
Main event	October 2016	Kloten, Switzerland	BCI, FES, ARM, LEG, EXO, WHL	BCI: 11 FES: 11 ARM: 10 LEG: 12 EXO: 7 WHL: 11	BCI: 10 FES: 10 ARM: 8 LEG: 7 EXO: 6 WHL: 9
Series	May 2019	Karlsruhe, Germany	ARM, LEG	ARM: 5 LEG: 3	ARM: 5 LEG: 3
Series	May 2019	Kawasaki, Japan	WHL	8	4
Series	September 2019	Graz, Austria	BCI	6	5
Main event[a]	May 2020	Kloten, Switzerland	BCI, FES, ARM, LEG, EXO, WHL	BCI: 15 FES: 12 ARM: 20 LEG: 15 EXO: 20 WHL: 12	BCI: 12 FES: 11 ARM: 13 LEG: 12 EXO: 18 WHL: 6
Main event[b]	November 2020	Decentralized	BCI, FES, ARM, LEG, EXO, WHL	BCI: 7 FES: 9 ARM: 13 LEG: 5 EXO: 9 WHL: 7	BCI: 8 FES: 9 ARM: 10 LEG: 4 EXO: 5 WHL: 3

Abbreviations: ARM, Arm Prosthesis Race; BCI, Brain–Computer Interface Race; EXO, Exoskeleton Race; FES, Functional Electrical Stimulation Bike Race; LEG, Leg Prosthesis Race; WHL, Wheelchair Race.
[a]This event was canceled due to the global COVID-19 pandemic; the indicated numbers are the numbers of teams and countries that registered for the event.
[b]This event replaced the canceled main event in May 2020 and was held in a worldwide, decentralized, multihub format. The indicated numbers are a subset of the numbers indicated for the canceled May event.

assistive technologies, BCIs are designed to acquire, process, and decode neural patterns and translate them into control signals for external actuators, ranging from computer spellers (9) to exoskeletons, telepresence robots (10), and powered wheelchairs (11). State-of-the-art BCI systems are based on a closed-loop architecture where the user is asked to perform specific mental tasks that are associated with distinct behaviors of the external application. Thus, neural signals can be recorded at different scales by means of invasive acquisition approaches, such as single- or multiunit array electrocorticography (12), or through noninvasive solutions, such as functional magnetic resonance imaging, functional near-infrared spectroscopy, or electroencephalography (EEG) (13). The signals are processed, and the most informative features are extracted and decoded by means of machine learning algorithms.

Despite the impressive achievements in this area, the translational impact of BCI technology is still limited. Indeed, current BCIs are not yet robust enough for daily operations by end users, often need close supervision by expert operators, and are rarely used outside laboratory and clinical settings. CYBATHLON offers the opportunity not only to directly face these challenges and evaluate BCIs in a real and demanding scenario, but also to push researchers to investigate new and effective solutions for everyday usage of this technology.

2.2. Description of the Discipline

In the BCI Races, pilots were asked to use their brain signals to control the behavior of their avatar in a computer game. While different races have used different games, the pilots were always asked to deliver up to three independent discrete commands (or no command) in order to maximize the speed of their avatar during the race. The races ended when the pilot's avatar reached the finish line or when the maximum race time had elapsed (240 s). The racetracks were composed of a sequence of four different task types, where pilots needed to deliver the appropriate command at the appropriate time. The rules allowed the use of any type of noninvasive and mobile method to record brain activity. The rules did not allow the avatar to be controlled with muscular or ocular artifacts, which produce strong signals that can be detected by a BCI system. Each team was required to provide the methodology used to remove such artifacts, and referees monitored pilots during the competition for voluntary facial movements (such as frowning or yawning) that would cause them.

So far, three BCI Race events have taken place. In total, 15 teams and 17 pilots from 13 countries have participated in these events (for details on the number of teams and countries represented in each event, see **Table 1**).

2.3. Devices and Methods

The section reports information about the BCI systems used by the teams in the three BCI Race events. The information was gathered from the studies published by the teams from 2017 to 2022 (14–22); however, not all teams disclosed details about the implementation of their BCI systems.

All teams exploited BCIs based on surface EEG signals. The number of channels ranged from 16 to 128. To control the BCI, 10 of 17 pilots (58.8%) relied on pure motor imagination (i.e., imagining moving a part of the pilot's body, such as moving their feet or opening or closing their hands); the other 7 (41.2%) used a hybrid BCI based on multimodal mental tasks (e.g., motor imagination and mental arithmetic, where the pilots mentally perform arithmetic operations such as subtractions). (As noted above, some teams did not reveal information about their approaches, and some pilots also participated in more than one competition; the percentages here and below are based on the pilots for which the relevant information was available.) To generate the three commands required by the game, 10 of 14 pilots (71.4%) relied on BCIs that exploited multiple mental tasks. Only two teams (BrainTweakers and WHi) exploited a BCI system based on two mental tasks (the imagination of the movement of the feet and the hands) and then used a decision-making strategy (based on the sequential delivery of two game commands in a short time window) to generate the third command (23, 24). EEG data processing and feature extraction were highly similar across all teams and relied on state-of-the-art methods widely known in the field. Finally, from the classification point of view, all teams exploited classical machine learning algorithms, which were based variously on linear or quadratic discriminative analysis (7 of 16 pilots, 43.8%), multiple binary classifiers (5 of 16, 31.3%), support vector machine (3 of 16, 18.8%), or logistic regression (1 of 16, 6.3%).

Furthermore, almost all pilots (14 of 18, 77.8%) had a training strategy strongly oriented toward machine learning, where the BCI decoder was recalibrated before each training session. The rationale was to exploit the latest recorded data in order to optimize the decoder and, thus, to achieve better classification performance. Only two teams (BrainTweakers and WHi) adopted a different approach by recalibrating the decoder only when accuracy started decreasing or when the pilot was unsatisfied with the performance of the system, which rarely happened.

Figure 2 provides an overview of the approaches applied by BCI Race teams.

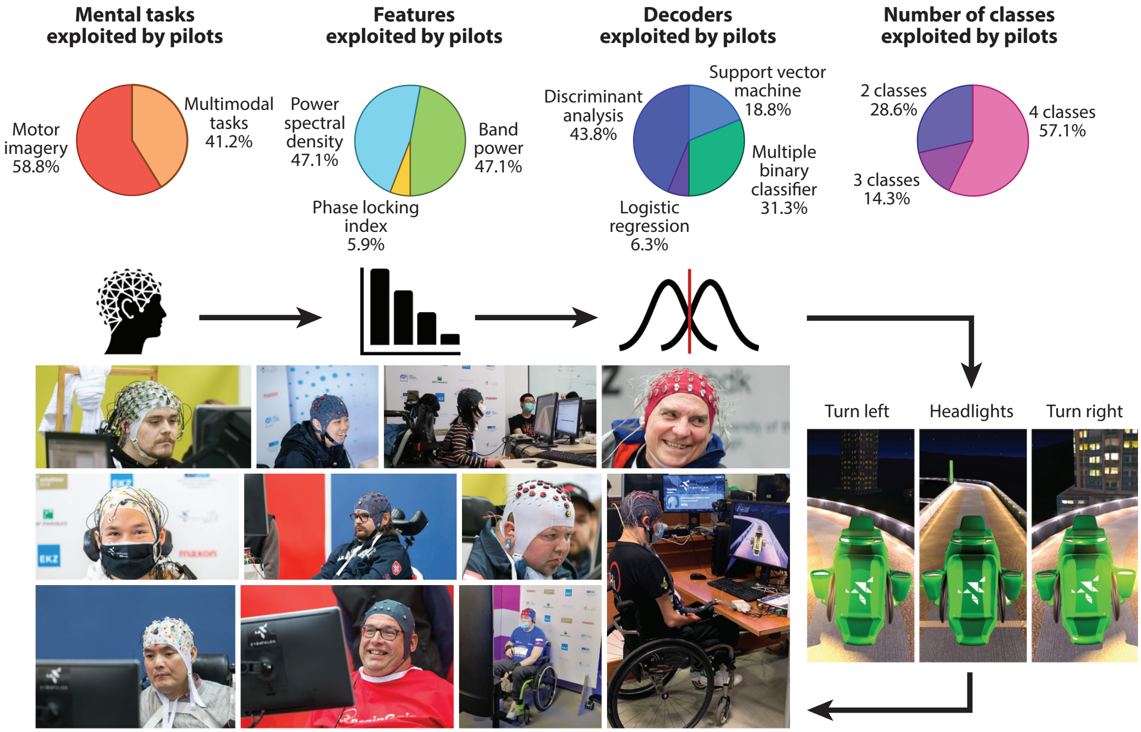

Figure 2

(*Top*) Breakdown of analysis approaches used by participating pilots to generate the signals to control the avatar in the CYBATHLON Brain–Computer Interface Race since 2016. Some teams did not disclose details about their implementations, and some pilots participated in more than one competition; the percentages are based on the pilots for which the relevant information was available. (*Bottom*) Pilots generating control signals for the game based on brain activity measured by surface electroencephalography. Photos provided by CYBATHLON/ETH Zurich.

2.4. Competition Results

In CYBATHLON 2016, BrainTweakers both obtained the best race time in the qualifiers (90 s) and won the final race (125 s). In the second event, CYBATHLON BCI Series 2019, the pilot from the WHi team won the qualifiers and the final by completing the race in 175 s and 183 s, respectively. Finally, in CYBATHLON 2020, the WHi team again won the gold medal with the best race time (172 s). The difference in race times between first and second place was particularly evident, especially in the case of the 2016 and 2019 events (31 s and 46 s, respectively).

2.5. Conclusion and Outlook

CYBATHLON has represented a unique opportunity both for researchers to rethink their BCI system in conditions close to daily usage and for end users to evaluate the technology in stressful scenarios. Reliability, efficiency, and efficacy have quickly become the most important objectives for the research groups.

The results presented here highlight two positive impacts on the applicability of BCIs. The first is enabling a user-centered design by involving the pilots months before the competition (14–16, 18) and carefully screening the pilots to tailor the system to their needs and skill. The second is a lower frequency of recalibrating (i.e., keeping the training scenario more constant). These two approaches reflect the current discussion in the BCI field—on the one hand, considering BCIs to be pure decoding tools and, thus, strongly focusing on the machine learning component of the system, and on the other hand, the idea that BCI is "a tale of two learners" (25), the user and the decoder. The bidirectional learning interactions between these two actors, referred to as mutual learning, is well known in the literature (26–28). Results in the three CYBATHLON BCI Race events seem to support using the latter approach to acquire robust and reliable BCI skills. However, the discussion is still open; for instance, it is still unclear how to make the decoder follow the user's learning curve and when the best moment for recalibration is.

The final consideration is more technical. BCI research has been conducted so far in highly controlled environments with expert operators handling possible technical malfunctions. However, in daily usage, technical faults should not happen—or at least their occurrence should be reduced to a minimum. Solutions explicitly designed for BCIs but inspired by other disciplines already exist and ensure the system's stability and reliability [e.g., ROS-Neuro (29–31)]. This will not only help to focus on more fundamental aspects of BCI research but would also be a demonstration of the maturity of the whole field.

For CYBATHLON 2024, implanted BCI systems will be eligible to participate for the first time. It will be revealing to see how surface-based BCIs will compare with the implanted approaches in the competition context.

3. THE FUNCTIONAL ELECTRICAL STIMULATION BIKE RACE

3.1. Background

Functional electrical stimulation (FES) delivers electrical pulses that induce contractions in muscles that are paralyzed due to an injury of the central nervous system. In FES cycling, a person with a spinal cord injury can propel a recumbent tricycle using their paralyzed lower limbs. The goal of this discipline is to showcase the use of FES and advance the devices and understanding of the underlying physiological challenges (32–35).

In FES cycling, the pilot sits in a tricycle with electrodes connected to their paralyzed legs. The electrodes relay electric pulses generated by a stimulator. A control system must activate different muscle groups in a coordinated manner to generate the leg movement that propels the tricycle.

Generally, the main challenge in using FES is to achieve selective action of muscles. Current FES technology synchronously activates multiple motor units, which results in rapid neuromuscular fatigue (compared with the fatigue experienced by healthy individuals) and hampers the control of muscle-force magnitude and movement. Furthermore, regular use of FES systems alters the user's muscular structure and response to electrical stimulation.

Sustaining a smooth pedaling motion while avoiding fatigue is therefore the goal in the FES Race. Teams must delve into FES delivery techniques and propose feedback control systems coupled with an adequate training program to achieve maximum performance.

3.2. Description of the Discipline

In the FES Race, pilots had to cover a predefined distance within a predefined race time limit. In CYBATHLON 2016, pilots had to cover a distance of 742 m within 480 s in an overground indoor racing track (36). To enable races during the COVID-19 pandemic, in CYBATHLON 2020 the tricycles were attached to indoor bike trainers to replicate the sensation of riding outdoors and to record the distance and time traveled. In this setup, the pilots had to cover 1,200 m within 480 s.

In CYBATHLON 2016, 11 teams from 10 countries participated in the FES Race; in CYBATHLON 2020, 9 teams from 9 countries participated (**Table 1**).

3.3. Devices and Methods

Teams were allowed to use any device that stimulated the neuromuscular structures of the lower limbs and fulfilled the standard regulations for electrical safety for biomedical devices. The tricycle had to be actuated solely by the pilot's leg. In both the 2016 and 2020 events, all equipment had to be attached to the pilot or tricycle and allow for untethered, nonstationary cycling.

Most of the teams used a standard system structure composed of an instrumented recumbent tricycle with crank angle measurement, an embedded CPU, push buttons, a user interface, and an electrical stimulator attached to the pilot with electrodes. Most teams also relied on commercially available programmable stimulators attached to surface electrodes placed on the skin for each muscle group, or single-electrode stimulation (SES), to deliver FES. Two teams used a pair of customized sleeves that contained the electrodes to facilitate placement and adherence (37, 38).

Multiple electrodes can also be placed on a single muscle group, known as spatially distributed sequential stimulation (SDSS). SDSS has shown performance improvement in a 6-min knee extension task (39). A comparison between SES and SDSS that simulated a race in the same setup used for CYBATHLON 2020 showed slight improvement with SDSS (40). However, a study that applied SDSS with the same indoor trainer used in CYBATHLON 2020 showed significantly lower performance by SDSS (41). These contrasting findings could be explained by the fact that the two studies used different FES controllers and different electrode placements. Ultimately, all teams used SES for the competition due to the complexity of the SDSS setup.

A few teams competed with a prototype FES stimulator. One team competed with a system that consisted of implanted electrodes, an implanted FES stimulator, and an external control unit. Implanted electrodes allow selective targeting of nerves to stimulate specific muscle groups and relate to an increase of approximately 25% in power produced in comparison to surface electrodes (42, 43). At the same time, however, they require surgery for permanent placement and are prone to infection; therefore, their setup and maintenance are complicated, and they require frequent medical follow-up.

Conventionally, FES onset is determined by the crank position, which is measured by an encoder or an inertial measurement unit. Inertial measurement units can also be placed on the pilot's legs to directly measure the knee angle (38, 44) or thigh inclination, indicating the knee flexion or extension phase (45, 46), as input in the FES control system. Mechanomyography sensors have been used to monitor muscle activity in real time during stimulation and supervise muscle fatigue (47, 48). Several teams have incorporated force sensors into the tricycle pedals to improve their stimulation algorithm, aiming to enhance performance by measuring muscle fatigue (48, 49). The strategy for modulating the FES stimulation diversified considerably from CYBATHLON 2016 to CYBATHLON 2020, ranging from manual on/off controllers for stimulator or interval pedaling, to simple proportional–integral–derivative controllers for cadence control, to complex reinforcement learning–based autotuning controllers with fatigue as the control variable (37, 39, 44, 50–53).

Figure 3 provides an overview of standard FES cycling components and enhancements proposed by FES Race teams.

3.4. Competition Results

In CYBATHLON 2016, Team Cleveland won with its implanted system. In CYBATHLON 2020, both the first- and second-place teams used a completely commercially available device.

Teams that participated in both events saw a general increase in performance. In 2020, pilots raced in an indoor trainer, resembling an ergometer, which was designed to simulate overground cycling and is used by elite cyclists to enrich conventional training. Therefore, although the pilots

Figure 3

Overview of standard components for functional electrical stimulation cycling used by most participating teams in the CYBATHLON Functional Electrical Stimulation Bike Race (*top*) and enhancements proposed since CYBATHLON 2016 (*bottom*). Images of standard components adapted with permission from Reference 41; image of implanted electrodes adapted from Reference 42 (CC BY 4.0); image of multiple surface electrodes adapted with permission from Reference 41; images of suit with integrated electrodes and pedal force sensor adapted with permission from Reference 37; image of mechanomyography sensor adapted with permission from Reference 48; images of inertial measurement unit sensor and crank force sensor adapted from Reference 49 (CC BY 4.0); central photo provided by CYBATHLON/ETH Zurich.

were not racing overground, the overall increase in performance should be credited mostly to the improvements in system design and the pilot's fitness.

3.5. Conclusion and Outlook

Between the 2016 and 2020 FES Races, the methodological and technological methods matured enormously, from simple manual triggering of FES to automated control algorithms (54). In CYBATHLON 2020, teams used a wider range of methods in comparison with the 2016 competition (36). Team Cleveland won the 2016 event by a huge margin and came in third in the 2020 event. Due to the geographic separation from the team during the pandemic, this particular pilot had very little time to prepare for the competition. This situation showcases the contrast between the proven technical and physiological advantages of a complex approach (the implanted electrode) and the potential availability for training and ease of use of a simpler system (the surface electrodes).

For FES cycling to become more accessible to users, the system designs need to be simplified. Currently, the setups require at least one assistant to place the electrodes and help the pilot transfer into the tricycle.

Regarding FES delivery, a trend that could be applied to this CYBATHLON discipline is spinal cord stimulation, which has demonstrated the ability to restore gait in individuals with a spinal cord injury. The rule book for CYBATHLON 2024 allows this approach.

There has been no wide clinical trial with a broad population for long-term assessment of the alleged benefits of FES cycling. The CYBATHLON initiative contributes to the availability of systems that could potentially be used in such trials.

Finally, the FES knowledge and advancements gained from the competition format will directly impact other applications of FES, such as neuroprostheses. These are devices that use electrodes to interface with the nervous system and aim to restore functions that have been lost due to disease or injury.

4. THE ARM PROSTHESIS RACE

4.1. Background

The loss of an upper limb leads to reduced autonomy in activities of daily living, work, and social interaction. Upper-limb prostheses represent a valid support to restore some of these lost capabilities (55). Powered solutions offer a more functional replacement for grasping and manipulation activities (56) as compared with cosmetic prostheses (57). Although body-powered prostheses are simple and have limited dexterity, they are valued for their robustness and control reliability. These systems operate by means of a cable control system that encompasses one or both shoulders and typically allows one control input to actuate a hook-like gripper. Externally powered prostheses, by contrast, range from simple, anthropomorphic, gripper-like solutions to more sophisticated devices. While simple solutions provide a grip with a single shape, most advanced bionic prostheses allow coordinated finger motions and a broader set of grasping patterns. Advanced prostheses are usually equipped with only two surface electromyography sensors and adopt additional strategies, such as muscle cocontraction or smartphone control, to switch between grasping modalities, although these switching strategies tend to be rather unnatural and place a higher cognitive burden on the user. Each solution has diverse benefits and drawbacks, and different prosthetic technologies may be preferred depending on the specific domain, residual muscle condition, and cultural aspects.

Beyond replacing all the sensory-motor functions and the aesthetic appearance of the missing limb, other fundamental requirements of upper-limb prostheses relate to the intuitiveness and reliability of the devices in everyday tasks and challenging situations (58). Despite the promising technological developments of the last two decades and the optimistic perceptions of media and advertisements, current solutions and control methods are far from being comparable to the extraordinary functionalities of biological limbs (59).

4.2. Description of the Discipline

In the ARM Race, pilots with a uni- or bilateral transradial limb amputation were equipped with a prosthetic hand or arm and were asked to complete six tasks in the shortest time possible (with a time limit of 480 s). Each task was inspired by activities of daily living, such as preparing breakfast or doing laundry, with the goal of highlighting challenges and barriers encountered by the users in everyday life. The focus was on testing the grasping functionalities (i.e., switching between grip types, manipulation skills, and grip force and precision), the reliability of the control method (i.e., in different arm configurations or while holding an object), and multijoint coordination (i.e., manipulating objects with both hands at the same time). In CYBATHLON 2020, one of the tasks was specifically designed to promote the use of haptic feedback. While some tasks encouraged the coordinated use of both arms, in others, the pilots were challenged to exclusively use the prosthesis. Teams were allowed to use any passive or active systems (including invasive and noninvasive control methods).

In total, 23 teams from 18 countries participated in the CYBATHLON 2016 and 2020 ARM Races, and 5 teams and 6 pilots competed during the 2019 ARM Series in Karlsruhe, Germany (**Table 1**). In 2016, most teams used a commercially available prosthesis, and only 2 teams used a prototype from a research laboratory; in 2020, there was an increased use of noncommercial hand solutions, with 8 out of 13 participants competing with a research prototype.

4.3. Devices and Methods

Although standard solutions such as common body-powered or direct myoelectric control have been used in the ARM Race, encouraging results in novel design directions were visible during CYBATHLON 2016 and CYBATHLON 2020.

From the mechanical point of view, one promising approach consists of underactuated systems. In these devices, the number of degrees of actuation is smaller than the number of degrees of freedom (DOFs) (e.g., 60) while still preserving high flexibility in grasping. In the field of myoelectric control, surgically implanted electromyography electrodes, machine learning to decode users' intentions, or novel alternatives to surface electromyography sensors (e.g., the use of force sensors or mechanomyography) were used by some of the participating teams in CYBATHLON 2016 and CYBATHLON 2020 (61–63).

From the clinical point of view, novel progress toward bionic integration has been based on successful and innovative surgical techniques. One major advancement consists of the physical connection of the prosthesis directly to the residual skeletal structures, termed osseointegration. This technique, combined with implanted electromyography sensors, has been incorporated into commercial devices (Teams x-OPRA and e-OPRA) and showed great performance during CYBATHLON 2016 and CYBATHLON 2020 (61). Participants also explored new techniques and solutions to restore sensory feedback (e.g., 64).

Figure 4 provides an overview of the different arm prosthesis components used by ARM Race teams.

4.4. Competition Results

The results from CYBATHLON 2016 and CYBATHLON 2020 suggest that minimalistic approaches in design and control could be more effective at addressing the problem of device reliability in a real-life scenario. However, that can also be the result of how the competition is designed in the first place. Despite their simple designs and limited grasp patterns, devices based on body-powered control approaches outperformed more advanced bionic prostheses and became the winning technology in most ARM Races: A hook-like solution won the race in 2016, and a more advanced four-finger gripper that allows the user to passively preselect the desired level of grasping force won in 2020. These results highlight the requirements of simplicity and reliability, which have been increasingly recognized by many research groups.

Figure 4

Overview of prosthesis components used by participating teams in the CYBATHLON Arm Prosthesis Race. Abbreviations: DOF, degree of freedom; EMG, electromyography. Photo of surface EMG sensors provided by Cristina Piazza; all other photos provided by CYBATHLON/ETH Zurich.

In CYBATHLON 2016, Team DIPO Power completed all tasks in the qualifiers and won the final race by scoring the most points. In second and third place were Team Michelangelo and Team e-OPRA, respectively; both teams scored the same number of points, but Michelangelo was faster. In CYBATHLON 2020, Team Maker Hand won the competition, while Team SoftHand Pro and Team e-OPRA finished in second and third place, respectively. While all three teams were able to fully complete the race, Maker Hand obtained the fastest overall time (344 s).

4.5. Conclusion and Outlook

In the field of arm prostheses, the trade-off between technical specifications and performance is influenced by several factors that are driven by the users' characteristics, attitudes, and personal preferences (65). Traditionally, innovative approaches are the result of intensive interdisciplinary collaborations between clinicians and engineers. The preparation for the CYBATHLON competition led to the promotion of an extensive human-centered design process (already suggested in Reference 65). The devices and control methods are designed and improved with the constant feedback of the pilots (58, 63, 64, 66). CYBATHLON combines a competitive context that requires extensive training for the pilot (61, 66) with an effective test bench for the system in real-world settings.

Each task included in the competition permits the evaluation of different aspects of the problem. Some of them focus on grasping and manipulation of objects with different sizes, shapes, and consistencies, promoting the use of different grip patterns. In other cases, they require bimanual coordination, such as tying a pair of shoes or opening a jar. Some of the proposed tasks involve grasping and manipulation actions in different arm postures—for example, grasping and releasing objects on a bookshelf, or performing the wire loop task—to validate the coordination between multiple joints and the reliability of the control method. All of these characteristics make the tasks of the competition a valid alternative to standard assessments for a preliminary evaluation of novel approaches in the laboratory environment (e.g., 67, 68).

Novel standard assessments based on the analysis of device functionalities in a daily-life context (e.g., the Assessment of Capacity for Myoelectric Control) have been used to evaluate the performance of each team from a clinical perspective. The remaining challenges point toward an efficient evaluation of research prototypes to ensure that academic promises can reach clinical reality. The key clinical needs include sensory feedback options, reduction of compensatory movements, and the development of adaptive systems for unstructured environments.

5. THE LEG PROSTHESIS RACE

5.1. Background

Recent technological advancements in the field of leg prostheses have increased the functionality and comfort of these devices, allowing for a higher quality of life for people with a lower-limb amputation. Expertise from mechanics, electronics, system engineering, and medicine have been combined to tackle the replacement of a human limb with an assistive device. Both scientific research and the prosthetics industry are currently pushing to develop artificial devices that are able to fully replicate the capability of the human body (69). The current focus of attention is considering both motor and sensory aspects of the limb loss together with the physical and mental embodiment of such external and artificial devices. The principal challenges guiding the development of the new generation of leg prostheses are related to (*a*) the mechanical interface between the artificial limb and the human body, to more effectively attach the device to the residual leg in a comfortable and safe manner (70, 71); (*b*) the neural interface, to connect the nervous system to the device in order to actively control device movement (72, 73) and simultaneously feel sensations coming directly from it (74–76); (*c*) the control, to build prosthetic devices that move exactly like human limbs (77); and (*d*) the multisensory interface, to build prosthetic devices that feel like natural limbs, fully integrated with the residual senses and fully incorporated by the users (78–80). The LEG Race aims to challenge users and their technologies during tasks that represent activities of daily living, pushing developers to design solutions that are mechanically optimized and consider user perspectives and preferences.

5.2. Description of the Discipline

Pilots in the LEG Race were required to have a transfemoral or through-knee amputation of at least one leg. Transfemoral amputees suffer a greater mobility reduction than transtibial amputees (81) due to the more proximal amputation and the lack of active knee joint control. The pilots were asked to perform six different tasks in the shortest time possible (with a time limit of 240 s). All tasks related to activities of daily living and targeted specific aspects of locomotion—namely, static and dynamic balance, stepping precision, mobility, agility, and stability (82). Pilots had to stand up from and sit down on a sofa, walk on rough terrains, balance on a narrow beam, climb stairs, and walk on ramps and laterally tilted paths. These tasks required pilots to precisely control the movements of their knee and ankle joints to place the prosthesis in a specific target location, and to heavily rely on the prosthesis support to reduce the load on the healthy leg.

In the LEG Series 2019 and CYBATHLON 2020 competitions, dual tasking (such as balancing unstable objects in the hand while walking or carrying bulky boxes while climbing stairs) was introduced to increase the pilot's cognitive burden or reduce their field of view, forcing the pilots to not focus only on their prosthetic leg. This is particularly relevant since daily activities are frequently performed in a dual-task context (83). To perform these tasks, teams could use both actuated and passive devices and any control strategy, including the electrical or mechanical instrumentation of residual body parts.

A total of 16 teams from 9 countries took part in the three LEG Races held to date (for details on the number of teams and countries represented in each event, see **Table 1**). In 2016, 9 teams came from companies and 3 came from academia; in 2020, 4 teams came from companies and 1 came from academia.

5.3. Devices and Methods

LEG Race teams have used 14 different devices, which exploited very different actuation and sensing principles as well as different control strategies. The technical specifications of the devices were often difficult to obtain due to the limited information released by companies on their websites and the scarcity of published literature.

Based on the actuation principle, we have classified the prosthetic devices as passive (with fixed spring and damping characteristics), microprocessor controlled (with adjustable spring and damping characteristics), or active (with external motors) (84). Three passive prostheses have been used in CYBATHLON events: Össur Total Knee, Circleg, and Rise Leg. The first consists of a polycentric knee joint based on a three-valve hydraulic system (85). The latter two use basic mechanics and were developed for low-income countries; Circleg is made of 3D-printed recycled plastic (86), and Rise Leg is a cane-based prosthetic leg (87). The microprocessor-controlled devices came from the key companies in the global prosthetics market—namely, Össur (Rheo Knee) and Ottobock Healthcare (Genium X3). The active prostheses consisted of one or two actuated joints. Teams Contur 2000, BionicM Inc., and Össur Power Knee competed with an active knee joint, providing knee flexion and extension. Team AMPFoot used an actuated ankle-joint prosthesis, providing a peak torque at push-off (88). Team VUB-CYBERLEGs' device contained series elastic actuators in both the knee and the ankle that provided knee flexion/extension and ankle plantarflexion/dorsiflexion (89). Compared with passive prostheses, active devices were expected to provide benefits when climbing stairs, lifting the leg over obstacles, and walking on tilted surfaces by relieving the load on the healthy leg (90). The pilot of Team VUB-CYBERLEGs reported a perceivable support in the sit-to-stand transfer; because his movements required less effort than those of other pilots, they were also visibly more natural (89).

We also identified a fourth group of prostheses: those that provide sensory information to the pilot. Team NeuroLegs was the only team that provided pilots with pressure information from the foot sole and knee angle feedbacks using a lightweight, noninvasive, and wearable technology that is an add-on for commercially available leg prostheses (91). Interestingly, leg amputees wear commercial prosthetic devices that do not give any sensory information about the interaction of the device with the ground or its movement. To this end, research has begun to place more focus on developing devices capable of providing artificial sensations using invasive and noninvasive wearable technologies (69, 77, 92, 93). Thanks also to the promising results achieved during the CYBATHLON race, the device developed by the NeuroLegs team is now moving toward commercialization (**https://my-leg.com**) and a clinical trial for device certification.

Figure 5 provides an overview of the different devices used by LEG Race teams.

5.4. Competition Results

Most teams were able to successfully complete all tasks. Walking on stones and walking up and down stairs were the most difficult tasks and had the highest failure rate.

In CYBATHLON 2016, the LEG Race was dominated by the three Össur teams. The team using the Rheo Knee microprocessor-controlled prosthesis placed first (660 points in 63 s),

Figure 5

Overview of types of transfemoral prostheses used by participating teams in the CYBATHLON Leg Prosthesis Race grouped by actuation principle. Photos provided by CYBATHLON/ETH Zurich.

followed by the teams using the Total Knee passive prosthesis (660 points in 66 s) and the Power Knee active prosthesis (660 points in 115 s). Due to the minimal difference in time between the first two teams (3 s), it is difficult to comment on the superiority of microprocessor-controlled or passive prostheses in performing the tasks. The microprocessor-controlled prosthesis was approximately 30% faster in the sit-to-transfer task, but the passive prosthesis was significantly faster in the hurdles.

In CYBATHLON 2020, four out of five teams obtained the full score and were ranked based on their time. The passive, low-cost prosthesis of Team Circleg won, completing the track in 163 s, followed by the sensorized prosthesis of Team NeuroLegs at 168 s. The two active prostheses by Contur 2000 and BionicM Inc. came in at 177 s and 233 s, respectively. Simpler prostheses performed better in the competition. The added sensation by Team NeuroLegs showed benefits in the tasks that required precise foot placement and great attention by the pilot (i.e., during foot placement on the stairs and the balancing beam).

5.5. Conclusion and Outlook

Prosthetics development has recently improved in quality of control, sensitization, and mechanics. Several research laboratories are showing the potential of powered knee (e.g., 94), ankle (e.g., 95, 96), and knee–ankle (e.g., 97, 98) prostheses to emulate human kinematics, avoiding compensatory movements, reducing the load on the healthy leg, and allowing users to avoid revealing their disability. The competitions on the road to CYBATHLON 2024 and the 2024 competition itself will target these open challenges by banning the control of the prosthesis by the hands and restricting space for maneuvering. Although the powered knee–ankle systems have the potential to further improve quality of life, they require more complex and coordinated control strategies. Recent advances in the development of natural and intuitive control approaches have been presented (72, 76, 99–101). Although these advanced approaches have shown promising results in research studies, very few commercially available prostheses have adopted these technological advancements so far.

Indeed, more sophisticated prostheses with active ankle and knee joints did not show markedly better performance than simpler devices during the competition. This is mainly because the time of task execution, rather than the quality of movement, was a fundamental factor in determining the race winner. More complex prostheses allow users to perform tasks more naturally and are expected to provide greater benefits to users during long-lasting activities of daily living that can hardly be replicated in an indoor competition setting.

6. THE EXOSKELETON RACE

6.1. Background

Robotic exoskeletons are active, mechanical, wearable devices that are anthropomorphic in nature to support the body and understand the motion intention of the user (102). In contrast to alternative devices, such as wheelchairs, exoskeletons enable paraplegic individuals to stand upright, walk, or climb and descend stairs. Prolonged use of a wheelchair can be accompanied by challenges to the user's general health, such as musculoskeletal symptoms in the arms and shoulders due to overuse, impaired blood circulation, or osteoporosis in the lower limbs due to the lack of loading in the seated position.

State-of-the-art lower-limb exoskeletons include three to five DOFs for each leg (103). Even though robotic exoskeletons for paraplegics have been in development since the late 1960s, the technology has lately benefited greatly from advances in actuators, sensors, and materials toward software control techniques and, more recently, artificial intelligence (104). Still, the technology has not matured enough to be accepted by end users for unsupervised daily-life use, and the usability of current exoskeletons is attenuated by two primary shortcomings. First, the limited situational adaptability of the movement patterns prevents a transfer from well-defined environments into open and chaotic daily-life situations. Second, current devices still rely heavily on extensive stabilization efforts by crutches and upper-body engagement (105), thereby limiting the use of the arms for additional task execution and increasing the cognitive load. To overcome this issue, state-of-the-art research has examined weight support and balance control methods (106), model predictive control (107), partial hybrid zero dynamics control (108), bioinspired standing balance control (109), and optimization of kinematic models (110).

Time-consuming and space-demanding sit-to-stand transitions further limit the usability of exoskeletons in daily life. Especially in public transportation, people are required to transition quickly between sitting and standing in areas with limited space.

Despite these shortcomings, robotic exoskeletons enabling an upright posture and gait for users with paraplegia have the potential to address many of the problems associated with prolonged wheelchair use. The ability to communicate with peers at eye level while standing is an often-mentioned and welcome additional feature of exoskeleton use, indicating that this technology also has a positive social impact.

6.2. Description of the Discipline

The EXO Race was designed for devices that enable paraplegic individuals to stand upright, walk, or climb and descend stairs, thus trying to restore the capability to perform activities of daily living. Pilots were asked to perform six different tasks in the shortest time possible (with a time limit of 600 s). Activities such as walking along a tilted path in an exoskeleton were challenging, requiring abduction/adduction in the hip and pronation/supination in the ankle. Sitting down and standing up were also challenging, as the pilots needed to keep their balance while generating and controlling substantial moments of the knee and hip joints. Climbing stairs and walking on surfaces that required irregular step lengths were challenging because the pilots needed to continuously control the positions of their feet. Assistive devices in this discipline needed to demonstrate automated gait capabilities, as load transfer to the ground via wheels or rolling contact was not allowed. The exoskeleton pilots have usually chosen adequate actions or gait patterns through a user interface. However, automated gait intention strategies (111) were also allowed. The exoskeleton joints could be active or passive.

In CYBATHLON 2016, 7 teams from 6 countries participated in the EXO Race; in CYBATHLON 2020, 9 teams from 5 countries participated (**Table 1**).

6.3. Devices and Methods

In CYBATHLON 2016, all seven teams used crutches, while in CYBATHLON 2020, eight of the nine teams used crutches; only one team was able to balance the pilot with the exoskeleton. Interestingly, this team actuated six of the seven DOFs for each leg. In CYBATHLON 2020, seven of the nine teams (78%) used exoskeletons with six or fewer actuated DOFs (three per leg, usually two actuators for the hip joint and one for the knee). **Figure 6** provides an overview of exoskeleton components used by EXO Race teams.

6.4. Competition Results

There is a linear correlation between the number of actuators and the device weight in the devices used in CYBATHLON 2020 (**Figure 7**). The average weight of all devices was 30 kg (61% higher than was reported in Reference 112). Furthermore, there seems to be a linear correlation between the device weight (and thus the actuation policy) and the total time spent during the race. Teams with more lightweight robots and fewer actuated DOFs achieved better times than teams with heavier robots.

6.5. Conclusion and Outlook

CYBATHLON has significantly contributed to the field by motivating teams to invest effort in improving sit-to-stand transitions and providing tasks that favor fast, lightweight exoskeletons. It has also highlighted the importance of training and gaining experience in piloting an exoskeleton, which were just as important as the technical realization of the robot (113). With the introduction of unpredictable elements in tasks, CYBATHLON 2024 aims to inspire teams to tackle the limited adaptability to real-world situations, as well as limited mobility, by introducing dual tasking that requires simultaneous walking and upper-body manipulation. To motivate the transfer into open and chaotic daily-life situations even further, CYBATHLON 2024 will introduce elements of unpredictability through the equitable randomization of tasks. Further focus will also be put on

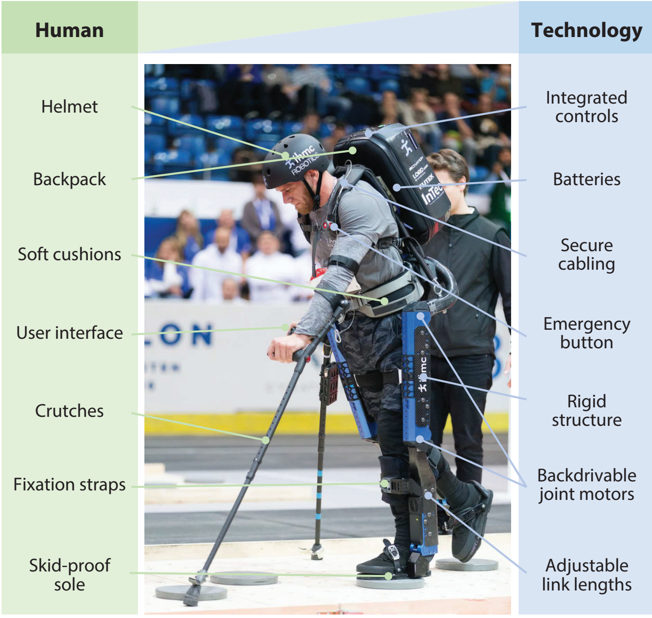

Figure 6

Overview of exoskeleton components used by participating teams in the CYBATHLON Exoskeleton Race. Photo provided by CYBATHLON/ETH Zurich.

sit-to-stand tasks with additional spatial constraints to inspire research on lightweight solutions, potentially eliminating the need for external aids such as crutches.

7. THE WHEELCHAIR RACE

7.1. Background

Wheelchairs are one of the most commonly used assistive devices to enhance the mobility of people with locomotor disabilities (such as paraplegia) and the elderly. Wheelchairs are needed by

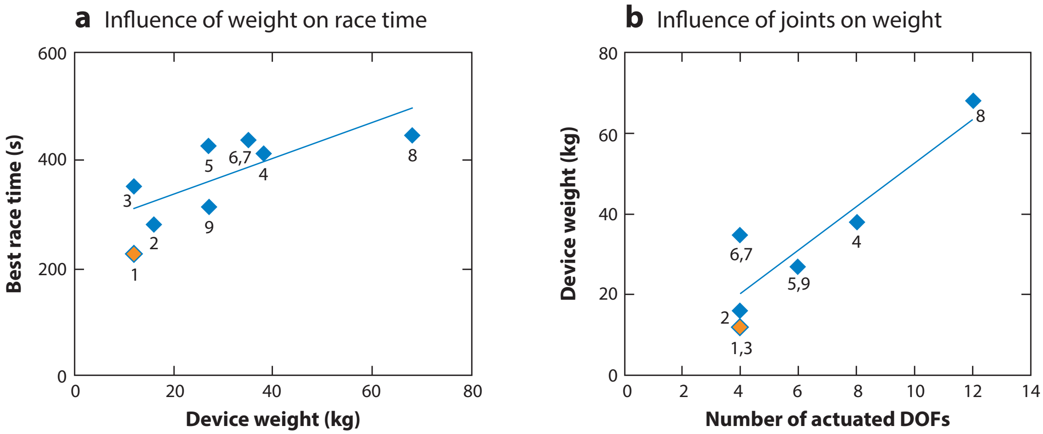

Figure 7

Positive linear correlations between (*a*) device weight and race time and (*b*) the number of actuated DOFs and device weight. Numbers under data points indicate final rank. Abbreviation: DOF, degree of freedom.

approximately 1% of the world's population, or more than 77 million people (114). While many regions of the world have regulations about accessible designs for building infrastructure, such as ramps to complement stairs, there are still countless buildings and sites that cannot be accessed by wheelchair users. Similarly, in nature there are many locations that cannot be readily accessed by wheelchair users. Powered wheelchairs with advanced mobility performance are needed to overcome such obstacles.

The aging population is expected to lead to an increase in the demand for electric wheelchairs with advanced mobility performance in the near future. Despite the high demand for wheelchairs worldwide, most models that are commercially available lack some of the functionalities that are relevant to daily-life use (e.g., to overcome single steps or staircases). Sometimes they are simply too bulky to be used in combination with standard furniture (e.g., when approaching a dining table). A lack of engagement with end users during research and development for powered wheelchairs has been reported (115). While several powered wheelchairs with advanced mobility performance (e.g., stair-climbing functions) have been commercialized in the last 10 years, most of them have disappeared from the market.

7.2. Description of the Discipline

In the WHL Race, pilots had to negotiate six tasks within the shortest time possible (with a time limit of 480 s). Each task emphasized a different aspect of daily-life wheelchair use. The set of tasks comprised challenges such as driving up and down steep ramps, climbing or descending staircases, negotiating uneven terrain, and navigating in a very confined space. CYBATHLON 2020 saw the addition of a task in which a door had to be opened and closed using an externally powered technical support system (e.g., a robotic manipulator).

From CYBATHLON 2016 to CYBATHLON 2020, the daily-life situations envisioned for the tasks remained mostly unchanged, but the technical capabilities required to perform these tasks increased. In particular, the technological difficulty significantly increased in two areas. First, the number of steps in the stairs task was increased from three (2016) to six (2020), which meant that the wheelchairs had to be able to move on a continuous series of steps. In the shorter staircase in 2016, only the front or rear wheels were engaged at a given time to ascend or descend the steps, whereas in CYBATHLON 2020, both the front and rear wheels were engaged at the same time. Second, the requirement of having an externally powered technical support system to open and close a door meant that teams also had to focus on adding a manipulator to their device while keeping the overall form factor compact. Research on wheelchair-mounted robotic arms has been conducted for several years (116–120), and some robot arms that can be mounted to wheelchairs are commercially available; for example, the six-DOF Jaco arm by Kinova (121) first launched in 2009. However, these manipulators are usually not paired with powered wheelchairs with advanced mobility functions (122).

In CYBATHLON 2016, 11 teams from 9 countries participated in the WHL Race; in the CYBATHLON WHL Series in 2019, 8 teams from 4 countries participated; and in CYBATHLON 2020, 7 teams from 3 countries participated (**Table 1**).

7.3. Devices and Methods

The level of powered wheelchair technology improved from the first (2016) to the third (2020) WHL Race. For example, progress has been made in terms of ability to negotiate the staircase. In CYBATHLON 2016, several participating devices were not equipped with a stair-climbing mechanism and had to skip this obstacle altogether. The climbing capacity of one mechanism was limited to exactly three steps, and only a few could have negotiated longer staircases at the time. In CYBATHLON 2020, the devices of all participating teams were technically able to climb staircases of infinite length.

An analysis of the mobility mechanisms used by the teams shows that many used a combination of approaches, although the four-wheel-type mechanism was the main one. For example, several teams combined a four-wheel-type wheelchair with a tracks mechanism mounted under the main chassis to combine the advantages of both approaches. When negotiating stairs, the tracks were lowered and used to lift the wheels off the ground (123). Scewo (**https://scewo.com**) applies self-balancing capabilities to a two-wheeled chassis and also uses tracks to negotiate stairs. However, combining wheels with tracks comes at the cost of losing time when switching between the two types of locomotion.

Some teams decided to forgo the wheels altogether and to base the locomotion of their device on tracks only, as this technology has good performance on rough terrain and stairs (e.g., 124). Because the length of the CYBATHLON racetrack is limited, the poor movement efficiency of the pure track approach is feasible. By contrast, the long-term use of daily-life application would likely favor approaches that are energetically more efficient and less abusive on the environment.

In CYBATHLON 2016, one team chose a distinct moving methodology by adding a roll axis to the rotational axes of the wheels, allowing the pilot to raise and lower the wheels on each side of the device (125). The resulting walking-like motion enabled the pilot to successfully climb stairs in all competitions.

In terms of size, all participating devices have been similar, and comparable in size to commercially available electric wheelchairs. The reason for this is that the rules require the powered wheelchairs to reach a table (more specifically, the wheelchairs must be able to move under a table so that the tabletop covers parts of the pilot's thigh without touching the table) and be able to pass through a door.

An analysis of robotic arms used in CYBATHLON 2020 shows that all but one team chose to develop their own prototype manipulator with relatively low power and basic position control through a joystick. This is likely related to the facts that the forces required to open and close the door in the CYBATHLON race were low and that the task was well specified. Many teams opened and closed the door by skillfully combining the robotic arm's motion with moving the powered wheelchair itself. Pilots needed to change the position of the wheelchair relative to the door because the door was opened and closed in a narrow space (approximately 1.2 m wide). Manually operating a robot arm requires a significant amount of skill and attention from the user. In the future, door opening/closing operations by robotic arms could be assisted by intelligent approaches that recognize parts of the door and plan and manipulate the door autonomously. The technological level at CYBATHLON 2020 had not reached that stage yet.

Figure 8 provides an overview of the different approaches used by CYBATHLON WHL Race teams.

7.4. Competition Results

The fact that several teams completed all tasks in both CYBATHLON 2016 and CYBATHLON 2020 suggests that the pilots were provided with functional devices and had the necessary practice for the competition. The winning team in both CYBATHLON 2016 and CYBATHLON 2020 was Robility Enhanced (named HSR Enhanced in 2016), which finished 5 s faster than the second-place team in 2016 and 57 s faster than the second-place team in 2020. The second-place team in 2020 was Caterwil, which also participated in both 2016 and 2020. The fact that both teams competed with the same pilot in 2016 and 2020 indicates that pilot skill and experience are important factors for success.

Figure 8

Overview of types of level-ground and stair-climbing locomotion used by participating teams in the CYBATHLON Wheelchair Race. (*a*) Split tracks for level-ground driving and stair climbing. (*b*) Self-balancing, two-wheeled driving on a tilted path. (*c*) Four-wheeled level-ground driving combined with an additional roll axis for stair climbing. (*d*) Four-wheeled level-ground driving using omniwheels. (*e*,*f*) Dedicated lifting mechanisms for stair climbing. Photos provided by CYBATHLON/ETH Zurich.

7.5. Conclusion and Outlook

The following are some of the next technological challenges that will be discussed in the WHL Race discipline as CYBATHLON continues:

1. In CYBATHLON 2020, most robotic arm operations were actively and manually controlled by the pilots. However, in the future, the integration of environment recognition and intelligent technologies will increase the proportion of autonomous arm operations. It will be critical to decide on the appropriate ratio between the pilot's control and the robot's autonomous operation.
2. With the introduction of spiral staircases for CYBATHLON 2024, the gradient of the surface will differ from left to right as the pilot climbs or descends the obstacle. Some form of level control for each side of the wheelchair will be critical to perform this new task successfully.

3. When moving on a sloped surface or across uneven terrain, powered wheelchairs tilt three-dimensionally, which can cause discomfort to the user. The addition of an attitude control to the seat will improve stability and user comfort.
4. The development of advanced user interfaces, such as eye-gaze-led driving (e.g., 126–129) and BCIs (e.g., 130–133), will also be actively considered as alternative user interfaces for pilots who are unable to use their hands to control the wheelchair due to their disability.
5. Cloud-based online analysis of use behavior and automated updating of device functions (e.g., by a mobile network) can optimize a wheelchair's performance based on data collected in a user's actual environment and during daily use.

8. OVERALL CONCLUSION

The purpose of this review is to shed light on how CYBATHLON has driven the field of assistive technology since the inaugural event in 2016. Below, we highlight some key aspects of the competition and how they have contributed to technological development.

8.1. Participation

CYBATHLON was born from the observation that the development of assistive technology often lacks input from end users, leading to dissatisfaction, frustration, and nonuse. Since the first event in 2016, CYBATHLON competitions have been held in different locations, mainly in Europe and Asia. While most of the participating teams in CYBATHLON 2016 were from industry or well-established research groups, CYBATHLON 2020 saw growing participation of enthusiastic teams of young students as well as teams from developing countries. The persistent and positive resonance by the field signifies an ongoing interest in and relevance of benchmarking outside of the laboratory and has generated important insights from the engineering, clinical, biomechanical, and user perspectives (134).

At the same time, CYBATHLON provides an important opportunity for participating teams to showcase the capabilities of their cutting-edge technology on a public international stage, which again increases the teams' fundraising opportunities. The interest by the media allows the dissemination of information about the challenges and opportunities of assistive technology to an audience beyond the scientific and clinical community. The support by international media outlets further drives the goal of improving the visibility, understanding, and perception of physical disabilities.

8.2. Relevance for Daily-Life Use

Assistive devices that are robust and generalize to dynamic, unstructured, and unforeseeable situations are required for daily-life use. Devices must also work reliably in functional corner cases. Device robustness is tested in the competition in a way that teams must be ready to perform at a predefined time and by attempting the tasks repeatedly over the course of an event. In the period from 2015 to 2020, the competition tasks were highly prespecified, and the aspect of generalizability of the device functions was tested to a lesser degree. Many teams developed task-specific functions (e.g., path control in exoskeleton gait), which do not generalize to more unstructured and unpredictable situations. Tailoring the technology for the well-defined conditions of the competition rather than for the actual daily-life situations conflicts with the intention of promoting assistive technology for daily-life use (135). From a performance perspective, it is comprehensible that some teams take this approach. Yet in daily life, environments are more diverse and unstructured, and devices must be versatile enough to cope with such situations. To motivate teams to develop more general solutions, future competitions will introduce unstructured tasks, for example, by randomizing the initial task conditions. To succeed in unstructured situations, it might be beneficial to use technologies that, on the one hand, can sense and recognize the context of their environment and, on the other hand, can detect their user's intention in an intelligent and autonomous manner (136).

For several disciplines, simpler and lighter devices with fewer DOFs (in the ARM and EXO Races) or even no active actuation (in the LEG Race) performed more successfully than more sophisticated devices. The limited number of DOFs requires more compensatory residual body motion, which is more tiring for the pilot and therefore not optimal during long-term use from an ergonomic perspective. However, since movement quality is not considered as a performance measure and the races are of limited duration (240–600 s), pilots using simpler devices can still outperform pilots using more complex and cutting-edge technologies. Movement quality will therefore be assessed and awarded at future competitions in several of the disciplines.

8.3. Contribution of the Pilot

It is known that the competent use of assistive technology requires training and adaptation from the end user (137), and the importance of intensive training for successful participation under the pressure of a competitive situation is also well known from sports. This is also the case for CYBATHLON, where the pilot contributes significantly to a team's performance. But—more importantly, from a daily-life perspective—the intensive training and competitive motivation ahead of the event led to increased home use in some cases (61, 138). This finding was further supported by individual narrations from pilots who reported that their perception of and confidence in their device have improved as a result of their preparation, even after being long-term users of assistive technology. Such results underline the importance of exercising with a new device and could also motivate users who are frustrated with their device to undertake extensive and ongoing training for everyday-life use.

8.4. Technology Transfer

An increased number of developers leads to a greater variety of technological approaches and more sophisticated assistive technologies. One can hypothesize that it also increases the chance of translating a technology from a prototype into a commercial product. At the same time, the technological transfer and translation to devices that can be used in daily life outside of the CYBATHLON competition remain a challenge. Over the past few years, several of the development initiatives participating in CYBATHLON have incorporated. Examples include MyLeg (**https://my-leg.com**), Scewo (**https://scewo.com**), TWIICE (**https://twiice.ch**), and Caterwil (**https://caterwil.com**). While these companies may not have been founded only because of CYBATHLON, they have likely profited from the publicity that resulted from their participation and from benchmarking against other devices in the same field.

8.5. User-Centered Design

As narrated by some of the past participants, the interdisciplinary composition of the teams brings together people and expertise that otherwise might not have interacted. The intense development and preparation process requires expedient communication across disciplines, thereby improving the mutual understanding of each other's perspective. This should also positively contribute to the development of appropriate assistive technology in the long run. A recent survey among CYBATHLON participants confirmed that the project appears to achieve its conceptual goal of promoting active user involvement in design and development, with 85% of pilots reporting that they were involved in the process (135).

In summary, CYBATHLON offers the unique opportunity to encourage user-centered design in a challenging context and to increase the number of studies and scientific contributions in the field of assistive technology, ranging from innovative solutions to the assessment of novel features (3). In the last few years, CYBATHLON has become a key event to promote diversity and social inclusion with a general audience and a showcase to highlight innovative interdisciplinary research and promising future directions. Technology can play a fundamental role in overcoming physical limitations and stereotypes. Here is where CYBATHLON and the role of developers become essential not only to match technologies with the users' needs, but also to improve how society relates to disability and assistive devices.

DISCLOSURE STATEMENT

L.J., C.B., Y.K.K., M.S., and R.S. are members of the organizing committee of CYBATHLON. R.R. is the founder and head of the strategic board of CYBATHLON. R.D.S.B. is the team manager of the CYBATHLON participating team EMA, C.B. is a former member of the CYBATHLON participating team NeuroLegs, P.C.-M. and C.P. are members of the CYBATHLON participating team SoftHand Pro, S.N. is the team manager of the CYBATHLON participating team RT-Movers, L.T. is the team manager of the CYBATHLON participating teams BrainTweakers and WHi, and G.V. is a member of the CYBATHLON participating team NeuroLegs.

AUTHOR CONTRIBUTIONS

L.J. authored Sections 1 and 8, revised Sections 2–7, created **Figures 1** and **8** and **Table 1**, and coordinated the overall preparation and revision of the manuscript. R.D.S.B. coauthored Section 3 and created **Figure 3**. C.B. coauthored Section 5 and cocreated **Figure 5**. P.C.-M. coauthored Section 4 and cocreated **Figure 4**. Y.K.K. coauthored Section 3. S.N. authored Section 7. C.P. coauthored Section 4 and cocreated **Figure 4**. M.S. authored Section 6 and created **Figures 6** and **7**. L.T. authored Section 2 and created **Figure 2**. G.V. coauthored Section 5 and cocreated **Figure 5**. R.R. and R.S. revised the entire manuscript.

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CYBATHLON would like to thank all teams participating in the competitions for contributing to a fully inclusive world in which every person with a disability has the freedom to choose the assistive technology they need and desire.

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Errata

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