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Review

Contributions of the Cybathlon championship to the literature on functional electrical stimulation cycling among individuals with spinal cord injury: A bibliometric review

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Abstract

Background: Due to its clinically proven safety and health benefits, functional electrical stimulation (FES) cycling has become a popular exercise modality for individuals with spinal cord injury (SCI). Since its inception in 2013, the Cybathlon championship has been a platform for publicizing the potential of FES cycling in rehabilitation and exercise for individuals with SCI. This study aimed to evaluate the contribution of the Cybathlon championship to the literature on FES cycling for individuals with SCI 3 years pre and post the staging of the Cybathlon championship in 2016.

Methods: Web of Science, Scopus, ScienceDirect, IEEE Xplore, and Google Scholar databases were searched for relevant studies published between January 2013 and July 2019. The quality of the included studies was objectively evaluated using the Downs and Black checklist.

Results: A total of 129 articles on FES cycling were retained for analysis. A total of 51 articles related to Cybathlon were reviewed, and 14 articles were ultimately evaluated for the quality. In 2017, the year following the Cybathlon championship, Web of Science cited 23 published studies on the championship, which was almost 5-fold more than that in 2016 ($n = 5$). Training was most often reported as a topic of interest in these studies, which mostly (76.7%) highlighted the training parameters of interest to participating teams in their effort to maximize their FES cycling performance during the Cybathlon championship.

Conclusion: The present study indicates that the Cybathlon championship in 2016 contributed to the number of literature published in 2017 on FES cycling for individuals with SCI. This finding may contribute to the lessons that can be learned from participation in the Cybathlon and potentially provide additional insights into research in the field of race-based FES cycling.

Keywords: Bike race; Exercise; FES cycling; Rehabilitation; Sports

1. Introduction

Cycling is a popular exercise modality for both healthy individuals and individuals with disabilities.[1] However, many individuals with disabilities experience limitations in their cycling activities and restrictions in their participation, which often results in difficulty in exercising and being physically active. Individuals with neurological diseases such as spinal cord injury (SCI) may experience paralysis and loss of body function below the level of the injury.[2] Prolonged immobilization due to muscle inactivity[3] and an inactive lifestyle[4] after SCI can induce secondary medical complications,[4] including heart disease and osteoporosis.[5]

Exercise among people with SCI is mostly limited to upper body exercise.[6] To involve the lower limbs during exercise among those with SCI, researchers often use functional electrical stimulation (FES) as a therapeutic exercise tool.[7] FES is applied over the skin surface of the muscles of the affected limbs in order to artificially activate paralyzed muscles[8] and produce functional movement.[9] FES can enable those with SCI to perform different functional tasks such as grasping,[10] walking,[10] standing,[11] transferring,[7] cycling,[12] and rowing.[13] Because walking and sitting-to-standing accomplished with the use of FES imposes the risk of falling in individuals with SCI,[14] researchers and clinical practitioners have favored FES-

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evoked cycling as an exercise therapy due to its safety. During FES-evoked cycling, electrical stimulation is applied to the overlying key muscles to provide the force needed to pedal the bike[15] at the correct force-producing crank angle. The main goal of FES cycling is to produce the highest possible force that will maximize health benefits.[16] Additionally, FES-evoked cycling provides individuals with SCI with an attractive therapy that promotes daily and leisure activities[17] and opportunities for practicing sport.[18]

To further promote the development of a suitable assistance system for daily use among individuals with physical disabilities,[19,20] a platform called Cybathlon was introduced in 2013. While the Paralympics only permit participants to use unpowered assistive technology, the Cybathlon promotes the use of powered assistive technology.[19] The 1st Cybathlon championship was held in 2016 in Zurich, Switzerland, and featured 6 different disciplines, or races, including an FES bike race.[21] In the discipline of FES bike racing at the 2016 event, SCI participants (as "pilots") competed with each other to promote the potential of technologies in contributing to exercise and fitness.[18] Participants cycled at maximum speed within a fixed distance of 750 m for 8 min.[22] They were not allowed to use their hands to crank the bike forward; thus, the propelling power could only come from their electrically stimulated leg muscles. The participant who completed 5 laps around the 750 m track in the fastest time, or who covered the most distance within the shortest time, was declared the winner.[23]

FES-evoked cycling, however, has a major drawback. The available literature indicates that FES-evoked cycling produces very low power and efficiency[24] in individuals with SCI when compared to healthy individuals. This is because of the limited muscle endurance due to early onset of muscle fatigue among SCI-affected individuals.[25] Hence, optimization of power production during FES-evoked cycling[26] results in increased fatigue resistance.[27] It has also been shown that FES-evoked cycling requires a more complex motion, making it difficult to stimulate the muscles accurately.[28] Therefore, optimal stimulation parameters[29,30] and accurate electrode placement overlying the key muscles are paramount if the muscle response to stimulation is to be maximized.[28] Consequently, the teams participating in the Cybathlon 2016 focused on their parameters of interest in order to improve their performance during FES-evoked cycling and win the race. Such parameters included the maximization of power; optimization of stimulation parameters or control systems, which included bike design and biomechanics; types of muscle stimulation and electrodes used; training protocol; and improvement of muscle strength or endurance.

To our knowledge, there has not been a bibliometric study that evaluated the contribution of the Cybathlon to the literature of FES-evoked cycling in individuals with SCI. Therefore, the purpose of this bibliometric review was to evaluate the effects of the Cybathlon 2016 championship, in particular the FES bike race category, on trends in the published literature on FES-evoked cycling among SCI-affected individuals over the 3 years pre and post the championship (i.e., 2013−2019). Specifically, the current bibliometric review sought to (1) evaluate the publication trends related to FES-evoked cycling before and after the Cybathlon, (2) evaluate the parameters of interest used by teams participating in the Cybathlon, and (3) assess the quality of the included studies. The current bibliometric study is important in that it identifies lessons that can be learned from the staging of the Cybathlon. Our hypothesis is that the Cybathlon contributed to changes in publication trends related to FES-evoked cycling studies because the event successfully generated substantial public interest, especially in technology.[20] Additionally, we hypothesize that the Cybathlon contributed to the selection of parameters of interest that optimized performance in FES-evoked cycling. Our findings may serve as a reference for future rehabilitative cycling studies.

2. Methods

2.1. Literature search strategy

A literature search was performed using the following databases: Web of Science (WoS), Scopus, ScienceDirect, IEEE Xplore, and Google Scholar. The search identified studies with findings published between January 2013 and July 2019. The following search terms, keywords, and phrases were used: "functional electrical stimulation", "electrical stimulation", and "functional neuromuscular stimulation" in combination with "cycling", "spinal cord injury", "paraplegic", and "paraplegia". A further search was conducted using the following search terms, keywords, and phrases: "cybathlon" in combination with "power", "optimization of stimulation parameters", "control system", "muscles stimulation", "electrodes", "training", "joint angle", "crank angle", "muscle strength", and "muscle endurance". Studies published in the English language and those that met the other eligibility criteria (see below) were retained for further analyses.

2.2. Eligibility criteria

Studies on FES-evoked cycling by individuals with SCI published between January 2013 and July 2019 were included in our review. The relevant keywords must have appeared in the title or abstract of the articles. However, keywords that were used in the title or abstract but that had a different meaning from the one intended for our review were excluded. To ensure accurate assessment of study quality, articles without their full text available were excluded. Duplicate articles were excluded, as were review articles and theses, because it was likely that they lacked adequate data for accurate assessment of study quality.

2.3. Data extraction from selected articles

An independent screening of the titles of studies potentially eligible for inclusion in this review was conducted by 2 of the review's authors (PNFH and NAH). Only articles that measured outcomes of FES-evoked cycling among individuals with SCI were retained and analyzed.

Three stages of review were conducted in order to answer 3 main questions. Stage I: were there any changes in trends in the literature about FES-evoked cycling after the staging of the

Cybathlon? Stage II: what were the features and parameters investigated in studies specifically about the Cybathlon? Stage III: what was the quality of the published studies about the Cybathlon?

2.4. Assessment of study quality

The quality of open access articles was assessed by 3 authors of this review (PNFH, NAH, and NAAR). The Downs and Black (D&B)[31] methodological assessment criteria were adapted to evaluate the quality of the final set of included studies. The D&B checklist consists of 27 items that address the following methodological components: reporting, external validity, internal validity (bias and confounding), and power (Supplementary Table 1). The score for each of the 27 items was either 0 or 1. Scores range from 0 to 28, with higher scores indicating a better methodological quality of the study. The following cut-points were used to categorize studies by quality: excellent (26−28, or 92.9%−100%), good (20−25, or 71.4%−89.3%), fair (15−19, or 53.6%−67.9%), and poor (0−14, or 0%−50%).[32]

Items 5 and 16 were removed from the D&B criteria (Table 1) because these 2 items were deemed irrelevant to the present review. The exclusion of some items from the D&B scale for grading the quality of included studies warranted normalization of the D&B score to 100%. In the event of disagreement or ambiguity regarding the grading of the quality of any included study, such cases were resolved by consensus after consultation with the senior author of this review (NAH).

3. Results

3.1. Characteristics of included studies

Initially, 4138 articles were retrieved for possible inclusion (Fig. 1). After title and abstract screening, 129 articles were retained for Stage I review. A total of 51 articles that specifically related to the Cybathlon were included in the Stage II review. Finally, for Stage III review, 14 studies related to the Cybathlon were included for assessment of study quality.

3.2. Trends in the literature on FES-evoked cycling among individuals with SCI between January 2013 and July 2019

The database search revealed that 129 studies on FES-evoked cycling among individuals with SCI were published between January 2013 and July 2019 (Fig. 2). WoS cited the most studies on FES-evoked cycling among individuals with SCI between January 2013 and July 2019 ($n = 57$), while IEEE Xplore cited the least ($n = 8$). However, all databases showed that fewer than 10 studies on FES-evoked cycling were published each year between January 2013 and July 2019, except in 2017. After the staging of the Cybathlon event in 2016, WoS cited the highest number of studies in 2017 ($n = 23$), which was almost 5-fold more than that in 2016 ($n = 5$). The number of studies cited by Scopus also increased after the Cybathlon championship in 2016.

Table 1
Methodological quality of included studies according to Downs and Black checklist ($n = 14$).

Study	1	2	3	4	6	7	8	9	10	11	12	13	14	15	17	18	19	20	21	22	23	24	25	26	27	Quality score	Percentage (%)
Arnin et al., 2017[39]	1	1	1	1	1	N/A	0	N/A	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	0*	0	8/20	40.0
Berkelmans et al., 2017[23]	0	0	1	1	0	N/A	0	0	0	0*	0*	0	0	0	1	N/A	1	N/A	N/A	N/A	0	0	0	0*	0	4/20	20.0
Bo et al., 2017[41]	1	1	1	1	1	N/A	0	N/A	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	0*	0	8/20	40.0
Guimarães et al., 2017[33]	0	0	1	1	1	N/A	1	N/A	0	1	1	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	N/A	0	9/19	47.4
Laubacher et al., 2017[8]	0	1	1	1	1	N/A	0	0	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	N/A	N/A	0	0*	0	7/19	36.8
Leung et al., 2017[35]	1	1	1	1	1	N/A	0	N/A	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	N/A	0	8/19	42.1
McDaniel et al., 2017[6]	1	1	1	1	1	N/A	0	0	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	0*	0	8/21	38.1
McDaniel et al., 2017[37]	0	1	1	1	1	1	0	0	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	0*	0	8/22	36.4
Metani et al., 2017[22]	1	1	1	1	1	N/A	0	N/A	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	0*	0	8/20	40.0
Popovic-Maneski et al., 2018[38]	1	1	1	1	1	1	0	0	0	0*	0*	0	0	0	1	1	1	1	0*	0*	0	0	0	0*	0	10/25	40.0
Sijobert et al., 2017[34]	1	1	1	N/A	1	N//A	1	0	0	0*	0*	0	0	0	1	1	1	1	0*	N/A	N/A	0	0	0*	0	9/21	42.9
Tong et al., 2017[36]	1	0	1	1	1	N/A	0	0	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	N/A	0	7/20	35.0
Wiesener et al., 2016[42]	1	1	0	1	1	N/A	0	0	0	0*	0*	0	0	0	0	N/A	1	1	N/A	N/A	0	0	0	0*	0	6/21	28.6
Wiesener et al., 2017[40]	1	1	0	1	1	N/A	0	N/A	0	0*	0*	0	0	0	1	N/A	1	1	N/A	N/A	0	0	0	0*	0	7/20	35.0
Average																										107/287	37.3

Notes:
Downs and Black criteria are summarized as: 1 = hypothesis/aim stated; 2 = outcome described in introduction/method; 3 = participants' characteristics described; 4 = intervention described; 6 = findings described; 7 = data distribution reporting; 8 = description of adverse events; 9 = description of participants lost to follow-up; 10 = exact p-value reported; 11 = description of participants' selection; 12 = participants represented entire population; 13 = appropriateness of the experimental facility; 14 = blinding of the participants to the intervention; 15 = blinding of the examiner; 17 = Adjustment of analysis period; 18 = appropriate statistics used to measure outcomes; 19 = adherence to the intervention; 20 = accuracy of outcome measures; 21 = population of participants' intervention; 22 = period of participants recruited; 23 = participants' randomization; 24 = randomized intervention assignment; 25 = adjustment for confounding in the analyses; 26 = participants lost to follow-up reported; and 27 = sufficient power detected. Each criterion has a maximum of 1 point. Points were awarded only when the criteria were clearly described. Score 1 = Downs and Black criteria met; Score 0 = Downs and Black criteria unmet; Score 0* = unable to determine. N/A = criteria is not applicable to the study.

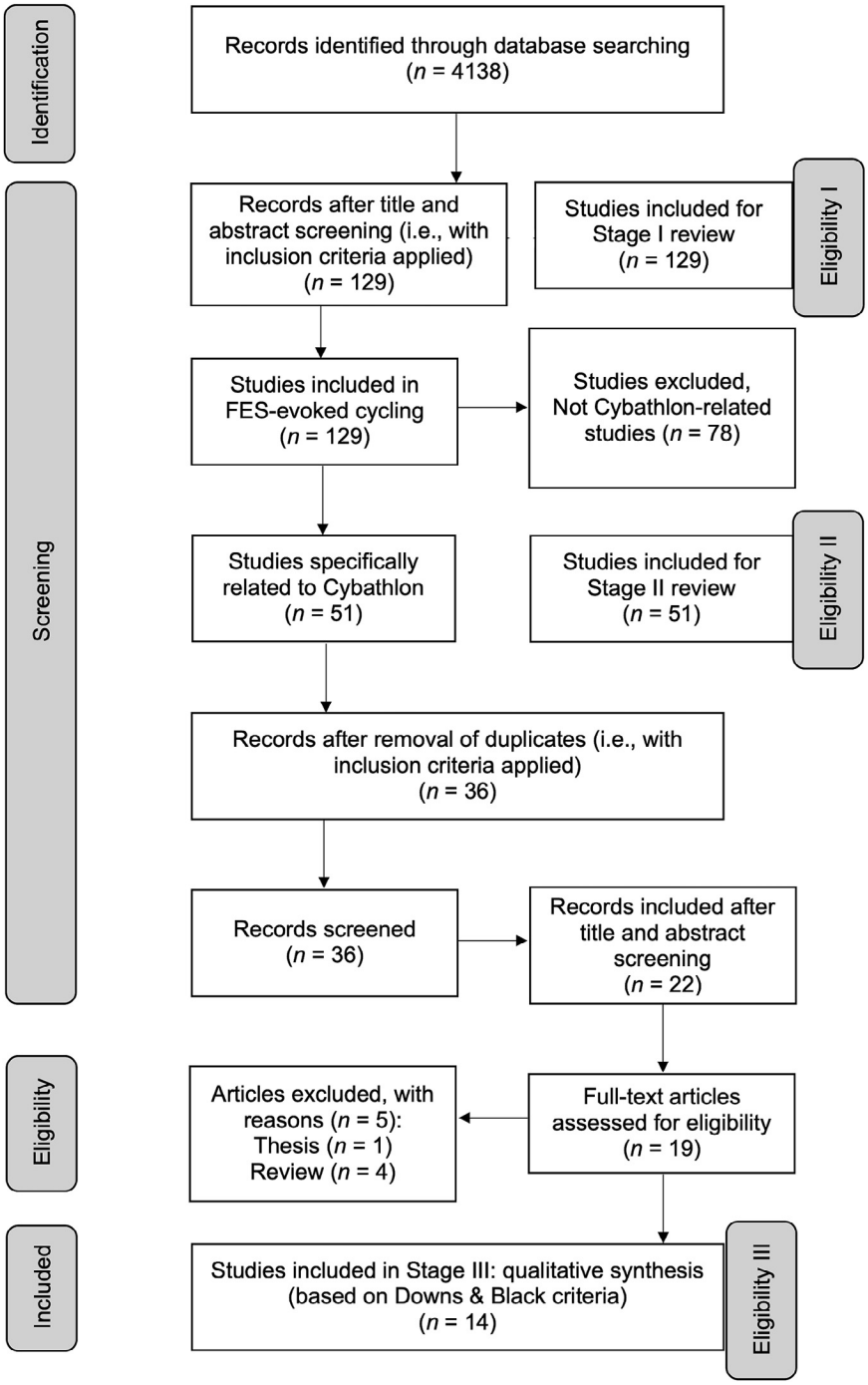

Fig. 1. Screening process for studies included in this bibliometric review. Stage I: trends in literature on functional electrical stimulation (FES)-evoked cycling published after the Cybathlon. Stage II: features and parameters investigated in publications specifically related to the Cybathlon. Stage III: Cybathlon study quality assessment.

3.3. Trends in the publication of studies related to FES-evoked cycling and the Cybathlon

Fig. 3 shows that 51 studies related to FES-evoked cycling in the Cybathlon were cited in all databases (Fig. 1). After the Cybathlon championship in 2016, WoS ($n = 13$), IEEE Xplore ($n = 3$), and Google Scholar ($n = 5$) cited the highest number of studies in 2017. Overall, the publication of studies cited in Scopus and ScienceDirect increased after 2016. However, publications cited in WoS declined gradually after 2017.

3.4. Geographical distribution

The geographical distribution of publications has become an interesting indicator of research productivity as it relates to individual countries, regions, and institutions. Fig. 4 shows the geographical distribution of studies related to FES-evoked cycling and the Cybathlon as identified in the WoS and Scopus databases. Most of the publications cited in WoS and Scopus originated from European countries (34.6% and 35.0%, respectively). Of the articles cited in the

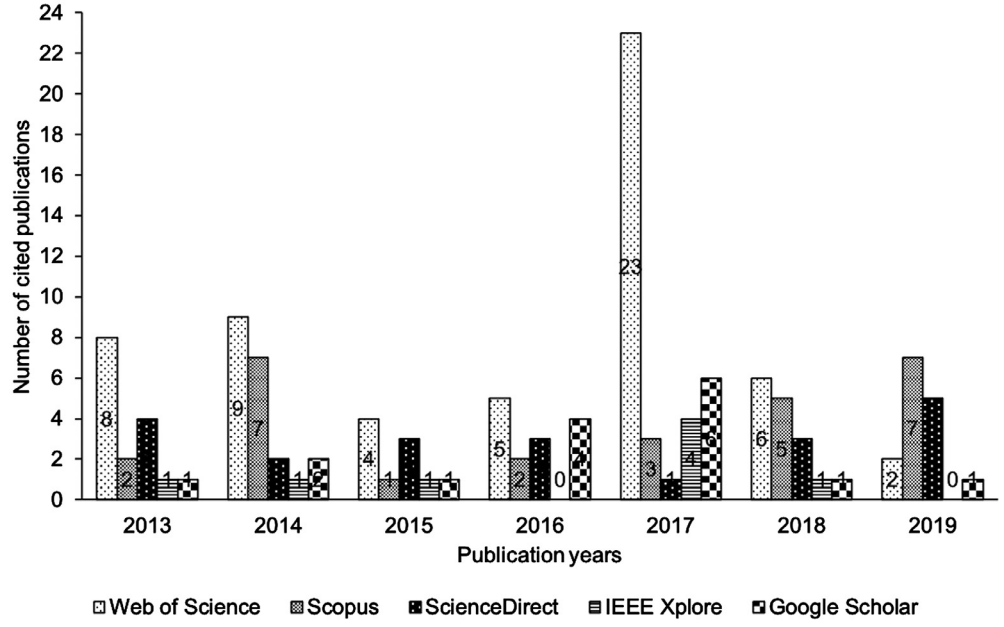

Fig. 2. Trends in the publication of functional electrical stimulation-evoked cycling studies between January 2013 and July 2019.

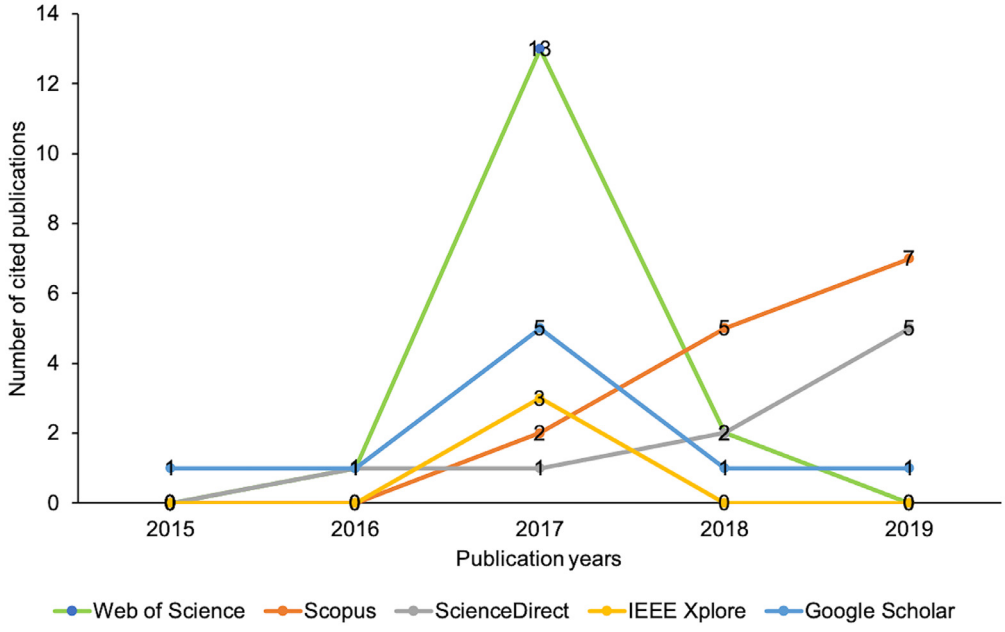

Fig. 3. Trends in the cited publication of studies related to functional electrical stimulation-evoked cycling and the Cybathlon.

WoS database (Fig. 4A), 19.2% were published in Asian countries, and 15.4% were published in South American countries.

Studies from the United States accounted for 11.5% of the publications, as did Switzerland. Australia and England accounted for 3.8% of the publications. Of the articles cited in the Scopus database (Fig. 4B), the United States accounted for 20.0% of the publications, followed by Asian countries (15.0%). South American countries accounted for 10.0% of the publications, as did Australia. Switzerland and Serbia each accounted for 5.0% of the publications.

3.5. *Publication types*

Supplementary Fig. 1 shows the frequency with which various types of publications related to Cybathlon were cited in WoS, Scopus, and IEEE Xplore. Articles were the type of publications most frequently cited in WoS ($n = 13$) and Scopus

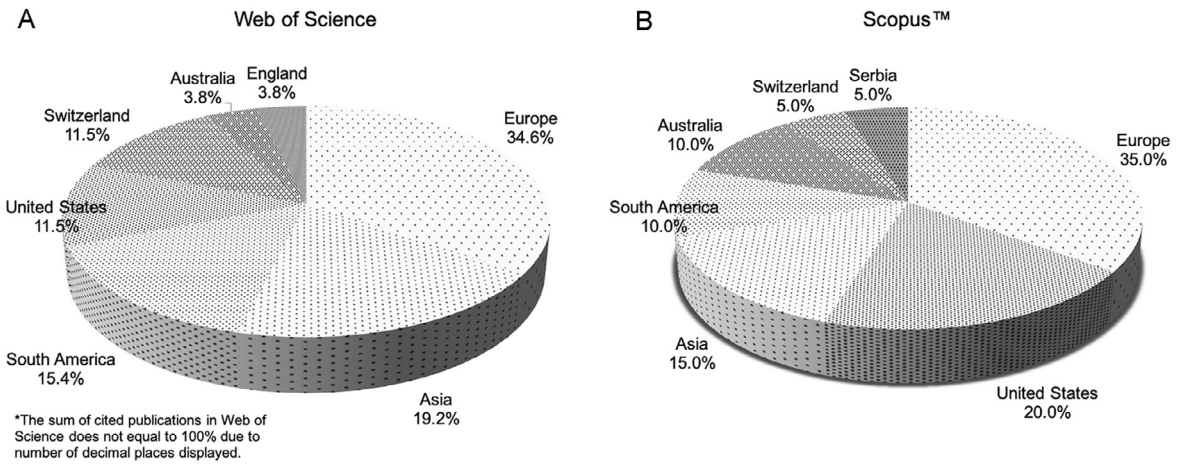

Fig. 4. Geographical distribution of publications related to functional electrical stimulation-evoked cycling and the Cybathlon. (A) Studies cited in the Web of Science database; (B) Studies cited in the Scopus database. The sum of cited publications in the Web of Science does not equal to 100% due to number of decimal places displayed.

($n = 12$). Magazine was the most frequently cited type of publication ($n = 2$) in IEEE Xplore. Proceedings papers were cited in WoS ($n = 2$) and IEEE Xplore ($n = 1$). The other types of publications reported in the databases were book chapters, editorial material, and reviews ($n = 1$ each).

3.6. Parameters of interest in the literature on FES-evoked cycling and the Cybathlon

Various parameters were the focus of the research covered in this review. In an effort to maximize the potential of participants in FES-evoked cycling and win the race, the parameters often were the main focus of the teams that participated in the Cybathlon and included the maximization of power, optimization of stimulation parameters or control systems, types of muscle stimulation, and electrodes used for this purpose, training, and improvement of muscle strength or endurance. Fig. 5 shows the number of publications in relation to the parameters of interest published in studies of FES-evoked cycling during the Cybathlon. The participating teams focused most on training as the parameter of interest (76.7%), followed by types of muscle stimulation and electrodes used (63.4%). Articles focusing on maximizing power accounted for 57.8% of the publications, while 41.8% of the publications focused on optimizing muscle stimulation or control systems. Improving muscle strength or endurance was the least reported parameter (27.9%).

3.7. Methodological quality

The mean of the D&B assessment (Table 1) of the included studies was 37.3% (range 20.0%–47.4%) and these were

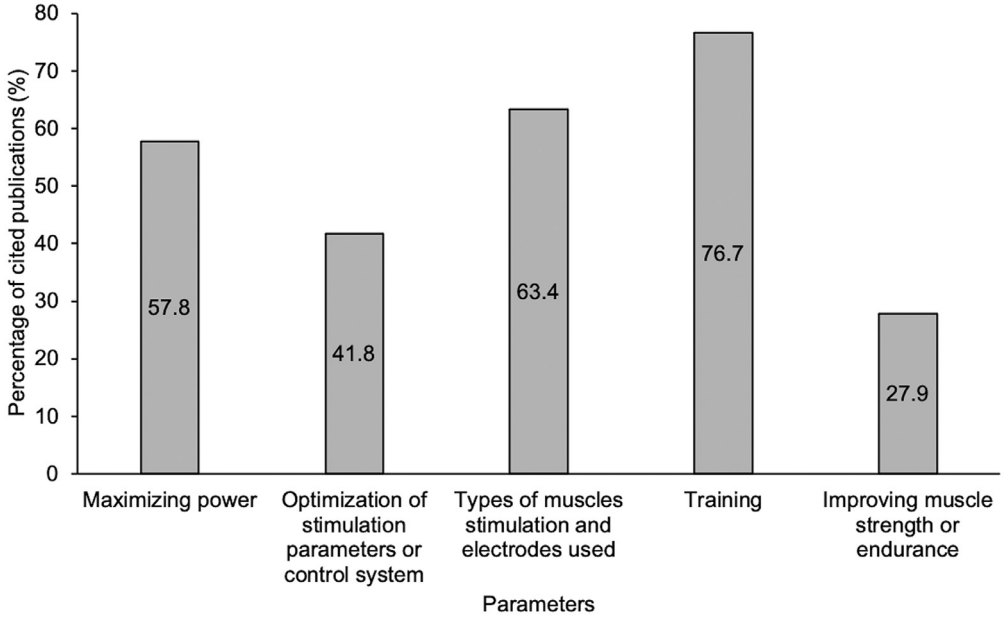

Fig. 5. Parameters of interest identified in the reviewed studies and focused on by teams participating in functional electrical stimulation-evoked cycling in the Cybathlon.

adjudged to be poor. Thus, the reviewed studies were deemed to be of low methodological quality.

None of the studies reported "actual probability value" (Criterion 10), "intervention was representative of that in use in the source population" (Criterion 13), "an attempt made to blind study subjects to the intervention" (Criterion 14), "an attempt made to blind the intervention outcomes" (Criterion 15), and "sufficient power to detect a clinically important effect" (Criterion 27). With the exception of reports from Guimarães et al.[33] and Sijobert et al.,[34] the studies did not report "adverse events that may be a consequence of the intervention" (Criterion 8). With the exception of work by Laubacher et al.[8] and Sijobert et al.,[34] the studies did not report "subjects randomized to intervention groups" (Criterion 23), and with the exception of the report from Laubacher et al.,[8] the studies did not report "randomized intervention assignment concealed from both patients and health care staff until recruitment was completed" (Criterion 24).

With the exception of work by Guimarães et al.,[33] the authors were unable to determine whether "subjects asked to participate in the study were representative of the entire population from which they were recruited" (Criterion 11) and "those subjects who were prepared to participate were representative of the entire population from which they were recruited" (Criterion 12). The authors of the studies were unable to determine whether "losses of patients to follow up taken into account" (Criterion 26), with the exception of Guimarães et al.,[33] Leung et al.,[35] and Tong et al.,[36] where the criterion was not applicable.

Criterion 7, "provide estimates of the random variability in the data for the main outcomes" was not applicable to the studies, except the work by McDaniel et al.[37] and Popovic-Maneski.[38] Criterion 18, "use appropriate statistical test to assess the main outcomes" also was not applicable to the studies, except for those from Sijobert et al.[34] and Popovic-Maneski et al.[38] Criterion 21, "the patients in different intervention groups (trials and cohort studies) or cases and controls (case-control studies) recruited from the same population" was not applicable to the studies, except it was unable to be determined for Sijobert et al.[34] and Popovic-Maneski et al.[38] Criterion 22, "study subjects in different intervention groups (trials and cohort studies) or cases and controls (case-control studies) recruited over the same period of time" was not applicable to the studies, except for the work by Popovic-Maneski et al.[38]

4. Discussion

This bibliometric review demonstrated that 39.5% of the total available FES-evoked cycling literature published between January 2013 and July 2019 was related to the Cybathlon (Fig. 1), and only 27.5% of the Cybathlon studies were included in the study quality assessment.[6,8,22,23,33–42] The low number of the Cybathlon studies included in the assessment of study quality was because duplicate titles were removed from the search of the 5 databases. Based on D&B criteria checklist[31] (Supplementary Table 1), only open access, full-length articles and conference proceedings were appropriate for the quality assessment. Other publication types, such as theses and review articles, provided insufficient information (e.g., regarding external and internal validity) and were thus inappropriate for quality assessment.

The present study sought to evaluate the publication trends related to FES-evoked cycling in the 3 years before and after the 1st Cybathlon championship in 2016. The largest number of FES-evoked cycling studies were published in 2017, the year following the Cybathlon championship (WoS, $n = 23$) (Fig. 2). Our review revealed that, in the WoS database, there was an almost 5-fold increase in the number of cited studies in 2017 than in 2016 ($n = 5$). The increase in publications in 2017 (Fig. 3) was because of the studies published from the Cybathlon participating teams ($n = 13$) in that year,[6,8,18,22,23,33–37,39–41] as shown in the findings from the present study (Table 1). Because the Cybathlon championship encouraged the exchange of information among people with disabilities, the general public, researchers, and developers of equipment,[43] the blending of technology and clinical neurorehabilitation science gained vast attention and thus contributed to the increase in the number of studies.[44] Our review also revealed that the Cybathlon championship led to an increase in the publication of studies related to FES-evoked cycling shortly after the event, but not for an extended period afterward. Our results partially support our initial hypothesis that the Cybathlon championship would contribute to an increase in the publication of FES-evoked cycling studies. To our knowledge, no studies have yet evaluated the contribution of the Cybathlon to FES-evoked cycling studies.

The Cybathlon showcased the technologies available for the promotion and enablement of exercise participation and fitness training for individuals with disabilities.[18] Our review revealed that the Cybathlon studies mostly originated from European countries (WoS = 34.6%; Scopus = 35.0%) (Fig. 4).[18,23,34,40] This may be due to the rapid development of technologies in sport rehabilitation for individuals with SCI in European countries. It is important to note that most of the FES cycling devices in rehabilitation industries around the world are imported from European countries such as Germany and the Netherlands. MOTOmed (Reck-Technik GmbH & Co. KG Medizintechnik, Betzenweiler, Germany) and BerkelBike (BerkelBike BV, Sint-Michielsgestel, the Netherlands) are the commercialized FES-assisted cycling ergometers that are widely used in rehabilitation industries.[45] Our review revealed that Cybathlon studies were conducted in many different locations, including Asian countries,[18,35,36,39] South American countries,[18,45] the United States,[6,18,37] Switzerland,[8,18,46] Australia,[18] England,[23] and Serbia.[22] The wide geographical distribution of Cybathlon studies indicates that FES-evoked cycling is well-researched throughout the world and well-accepted among people with disabilities across different cultures.[43] An event like the Cybathlon championship provides the opportunity for participating teams from throughout the world to promote their own technologies and to compete against other ones. Individuals with disabilities, rehabilitation industries, and researchers throughout the world can benefit from the Cybathlon championship.

Our review established that articles, compared to other types of publications (Supplementary Fig. 1), on the Cybathlon

were more frequently cited in 3 of the 5 databases we searched. The articles cited were authored by the participating teams in 2017[8,18,22,23,33–35,37,39–41,45,46] and describe various aspects of the race, including information on the pilots, stimulation strategies, bike details, and training programs.[37] The other types of publications, such as papers from proceedings,[36,42] book chapters,[45] editorial material,[6] and reviews,[47] were published in similar quantities.

4.1. Parameters of interest among publications

The present review also sought to evaluate the parameters of interest that teams participating in the Cybathlon used to improve the efficiency of FES-evoked cycling. To our knowledge, previous researchers have studied efforts to elicit maximum power during FES-evoked cycling to maximize the efficiency of FES-evoked cycling.[1,27–29,48–50] However, our review revealed that teams participating in the Cybathlon championship in 2016 also sought to elicit maximum efficiency during FES-evoked cycling (Fig. 5). Most of the participating teams (76.7%) focused on training individuals with SCI in preparation for the Cybathlon championship.[18] This may be because of the rule that required the Cybathlon participants to cycle at high speed for a longer distance for longer duration.[22] The training programs developed by the teams maximized the time they spent producing maximum power.[37] Therefore, stamina and consistency of the participants during FES-evoked cycling were paramount in winning the race. Our review revealed that most of the participating teams (63.4%) also focused on the types of muscles being stimulated and types of electrodes used.[36] This finding may be due to the difficulties in accurately locating and stimulating the muscles needed for FES-evoked cycling.[28] To maximize the efficiency of FES-evoked cycling during competition, more muscle groups needed to be stimulated.[48] The types and placement[28] of electrodes used in individuals with SCI can affect the efficiency of FES-evoked cycling. This was demonstrated by the winning team, that is, team Cleveland,[37] whose pilot was the only pilot who used an implanted stimulation system during the race. All the other teams used surface electrodes. The pilot's cycling pace was also consistent and smooth, thereby ensuring that the muscles were used efficiently and effectively throughout the race.

The present review revealed that in preparing for the Cybathlon championship, most of the teams (57.8%) focused on maximizing the power for FES-evoked cycling.[23] Previous researchers have reported that maximizing power production in FES-evoked cycling is important for maximizing efficiency as well.[50] Therefore, most of the participating teams focused on maximizing power in order to win the race. Our review also revealed that, instead of focusing on improving muscle strength or endurance, most of the participating teams focused on optimizing their stimulation parameters and control systems, including bike configuration and design.[39] Our findings in this area were not surprising; previous findings also showed that optimization of the stimulation parameters maximize the benefits from FES-evoked cycling[29] and minimize fatigue.[49] Studies have reported that modulation of stimulation parameters, such as frequency, current intensity, and pulse width, affect the muscle response to stimulation[28] and efficiency of FES cycling.[51] It has also been shown that adjusting the stimulation parameters can optimize power during FES-evoked cycling.[52] The power produced during FES-evoked cycling can be maximized, and muscle fatigue can be minimized, by using a lower stimulation frequency (less than 50 Hz)[53] and a higher pulse width (350 ms).[29] This strategy could be helpful to the participating teams in their efforts to win the race.

While the bike's mechanical design was not explicitly reported on in the literature as a parameter of interest for winning the race, we believe that this is also an important factor for winning. Most of the participating teams reported that the training and "human" characteristics of the pilot were important, just as the FES-related parameters were. A bike's mechanical design may well be a key factor in winning, and should be further investigated. Ankle joint fixation, which was reported to have influenced power production,[1] may also be an important factor. We observed that all bike pilots used a fixed ankle joint configuration, which most likely optimized force transfer and constrained non-sagittal hip motion.[37] However, further conclusions cannot be drawn without comparisons with different ankle joint configurations. Body inclination, power, and energy transfer from the muscles to the wheels and propulsion, as well as the overall bike weight and weight distribution, are all factors that should be considered when asserting that bike design is a chief contributing factor to winning the race.

4.2. Study quality

Our review also assessed the quality of the Cybathlon-related publications identified in our search. The reviewed studies were deemed to be of low methodological quality (37.3%). The lower scores for methodological quality may be due to the fact that many of the reviewed studies did not meet certain criteria, it could not be determined whether they met the criteria, and whether certain criteria were applicable to the studies. Most of the reviewed studies reported on the technical steps that their teams took in preparation for the Cybathlon championship; thus, no statistical analysis was performed. Only a few of the reviewed studies reported experimental outcomes, and none of the studies reported actual probability values. Similarly, most studies reported that only 1 participant—the Cybathlon FES "pilot"—was involved. Therefore, no randomization of participants occurred, and no attempt was necessary to be made to blind the study subjects to the intervention in the studies we reviewed.

While these factors may seem critical for rating the quality of the studies using D&B criteria, the reported outcome based on the rating items are nonetheless encouraging where case series or case studies are involved. Many descriptive and technological lessons can be learned from the reported studies, especially as the lessons relate to pilot selection and training, which has been underreported in race-based FES-evoked cycling. This is one of the clear contributions of the Cybathlon to the scientific literature.

5. Conclusion

This review describes the contributions of the 2016 Cybathlon championship to the literature related to FES-evoked cycling in individuals with SCI. Overall, our results may be useful in the fields of rehabilitation sports and FES-evoked cycling. The Cybathlon championship highlighted the potential of technology in exercise participation and fitness training for individuals with disabilities. Despite the brief period during which it contributed to the FES-evoked cycling literature, the Cybathlon provided insight into the parameters of interest the participating teams used in their efforts to maximize efficiency in FES-evoked cycling. This study provides information and lessons learned from the first Cybathlon that participating teams may find useful in preparing for future Cybathlons or similar championships. It is recommended that researchers investigate the social outcomes (i.e., leisure activities, activities of daily living, social interaction, community engagement, and quality of life) brought about by FES-evoked cycling and preparation for the Cybathlon. The present study could also be useful to researchers seeking to improve the performance of individuals with SCI involved in FES-evoked cycling.

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Authors' contributions

PNFH participated in the design of the study, contributed to data collection and analysis, and participated in interpreting the results; NAH participated in the design of the study, contributed to data analysis, and participated in interpreting the results; NAAR contributed to data analysis, and participated in interpreting the results; NH participated in interpreting the results. All authors contributed to the manuscript writing. All authors have read and approved the final version of the manuscript, and agree with the order of the presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

Supplementary materials

Supplementary materials associated with this article can be found in the online version at doi:10.1016/j.jshs.2020.10.002.

References

1. Hamdan PNF, Hamzaid NA, Usman J, et al. Variations of ankle-foot orthosis-constrained movements increase ankle range of movement while maintaining power output of recumbent cycling. *Biomed Tech* 2018;**63**:691–7.
2. Dolbow DR. Exercise following spinal cord injury: Physiology to therapy. *J Neurorestoratology* 2015;**3**:133–9.
3. Pette D, Vrbová G. Adaptation of mammalian skeletal muscle fibers to chronic electrical stimulation. *Rev Physiol Biochem Pharmacol* 1992;**120**:115–202.
4. Bloemen-Vrencken JHA, de Witte LP, Post MWM, van den Heuvel WJA. Health behaviour of persons with spinal cord injury. *Spinal Cord* 2007;**45**:243–9.
5. Topp R, Ditmyer M, King K, Doherty K, Hornyak J. The effect of bed rest and potential of prehabilitation on patients in the intensive care unit. *AACN Clin Issues* 2002;**13**:263–76.
6. McDaniel J, Lombardo LM, Foglyano KM, Marasco PD, Triolo RJ. Setting the pace: Insights and advancements gained while preparing for an FES bike race. *J Neuroeng Rehabil* 2017;**14**:118. doi:10.1186/s12984-017-0326-y.
7. Ho CH, Triolo RJ, Elias AL, Marasco PD, Triolo RJ. Functional electrical stimulation and spinal cord injury. *Phys Med Rehabil Clin* 2014;**25**:631–54.
8. Laubacher M, Aksöz EA, Bersch I, Hunt KJ. The road to Cybathlon 2016-Functional electrical stimulation cycling Team IRPT SPZ. *Eur J Transl Myol* 2017;**27**:259–64.
9. Meng L, Porr B, Macleod CA, Gollee H. A functional electrical stimulation system for human walking inspired by reflexive control principles. *Proc Inst Mech Eng Part H J Eng Med* 2017;**231**:315–25.
10. Popovic MR, Curt A, Keller T, Dietz V. Functional electrical stimulation for grasping and walking: Indications and limitations. *Spinal Cord* 2001;**39**:403–12.
11. Dzulkifli MA, Hamzaid NA, Davis GM, Hasnan N. Neural network-based muscle torque estimation using mechanomyography during electrically-evoked knee extension and standing in spinal cord injury. *Front Neurorobot* 2018;**12**:1–11.
12. Islam MA, Hamzaid NA, Ibitoye MO, Hasnan N, Wahab AKA, Davis GM. Mechanomyography responses characterize altered muscle function during electrical stimulation-evoked cycling in individuals with spinal cord injury. *Clin Biomech* 2018;**58**:21–7.
13. Andrews B, Shippen J, Armengol M, Gibbons R, Holderbaum W, Harwin W. A design method for FES bone health therapy in SCI. *Eur J Transl Myol* 2016;**26**:297–300.
14. Watanabe T, Tadano T. Experimental tests of a prototype of IMU-based closed-loop fuzzy control system for mobile FES cycling with pedaling wheelchair. *IEICE Trans Inf Syst* 2018;**101**:1906–14.
15. Davis GM, Hamzaid NA, Fornusek C. Cardiorespiratory, metabolic, and biomechanical responses during functional electrical stimulation leg exercise: health and fitness benefits. *Artif Organs* 2008;**32**:625–9.
16. Ragnarsson KT, Pollack S, O'Daniel Jr W, Edgar R, Petrofsky J, Nash MS. Clinical evaluation of computerized functional electrical stimulation after spinal cord injury: A multicenter pilot study. *Arch Phys Med Rehabil* 1988;**69**:672–7.
17. Perkins TA, de N, Donaldson N, Hatcher NAC, Swain ID, Wood DE. Control of leg-powered paraplegic cycling using stimulation of the lumbo-sacral anterior spinal nerve roots. *IEEE Trans Neural Syst Rehabil Eng* 2002;**10**:158–64.
18. Coste CA, Bergeron V, Berkelmans R, et al. Comparison of strategies and performance of functional electrical stimulation cycling in spinal cord injury pilots for competition in the first ever Cybathlon. *Eur J Transl Myol* 2017;**27**:251–4.
19. Novak D, Wolf P, Guglielmelli E. Cybathlon 2016: Showcasing advances in assistive technologies through competition. *IEEE Robot Autom Mag* 2017;**24**:122. doi:10.1109/MRA.2017.2757721.
20. Wolf P, Riener R. Cybathlon: How to promote the development of assistive technologies. *Sci Robot* 2018;3:eaat7174. doi:10.1126/scirobotics.aat7174.
21. Riener R. The Cybathlon promotes the development of assistive technology for people with physical disabilities. *J Neuroeng Rehabil* 2016;**13**:49. doi:10.1186/s12984-016-0157-2.
22. Metani A, Popović-Maneski L, Mateo S, Lemahieu L, Bergeron V. Functional electrical stimulation cycling strategies tested during preparation for the first Cybathlon competition: A practical report from team ENS de Lyon. *Eur J Transl Myol* 2017;**27**:279–88.
23. Berkelmans R, Woods B. Strategies and performances of functional electrical stimulation cycling using the BerkelBike with spinal cord injury

in a competition context (CYBATHLON). *Eur J Transl Myol* 2017; **27**:255–8.
24. Hunt KJ, Hosmann D, Grob M, Saengsuwan J. Metabolic efficiency of volitional and electrically stimulated cycling in able-bodied subjects. *Med Eng Phys* 2013;**35**:919–25.
25. Bickel CS, Gregory CM, Dean JC. Motor unit recruitment during neuromuscular electrical stimulation: A critical appraisal. *Eur J Appl Physiol* 2011;**111**:2399–407.
26. Hamdan PNF, Teo K, Hamzaid NA, Usman J, Razman R. The effects of releasing ankle joint on pedal force and power production during electrically stimulated cycling in paraplegic individuals: A pilot study. In: Ibrahim F, Cheong J, Usman J, Ahmad M, Razman R, Selvanayagam V, editors. *3rd International Conference on Movement, Health and Exercise*. Singapore: Springer; 2016.p.129–32.
27. Gibson H, Cooper RG, Stokes MJ, Edwards RHT. Mechanisms resisting fatigue in isometrically contracting human skeletal muscle. *Q J Exp Physiol* 1988;**73**:903–14.
28. Aksöz EA, Luder MA, Laubacher M, Riener R, Binder-Macleod SA, Hunt KJ. Stochastically modulated inter-pulse intervals to increase the efficiency of functional electrical stimulation cycling. *J Rehabil Assist Technol Eng* 2018;**5**:1–6.
29. Gorgey AS, Black CD, Elder CP, Dudley GA. Effects of electrical stimulation parameters on fatigue in skeletal muscle. *J Orthop Sport Phys Ther* 2009;**39**:684–92.
30. Kesar T, Chou L-W, Binder-Macleod SA. Effects of stimulation frequency versus pulse duration modulation on muscle fatigue. *J Electromyogr Kinesiol* 2008;**18**:662–71.
31. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health* 1998;**52**:377–84.
32. Hooper P, Jutai JW, Strong G, Russell-Minda E. Age-related macular degeneration and low-vision rehabilitation: A systematic review. *Can J Ophthalmol* 2008;**43**:180–7.
33. Guimarães JA, da Fonseca LO, de Sousa AC, et al. FES bike race preparation to Cybathlon 2016 by EMA team: a short case report. *Eur J Transl Myol* 2017;**27**:272–8.
34. Sijobert B, Fattal C, Daubigney A, Azevedo-Coste C. Participation to the first Cybathlon: An overview of the FREEWHEELS team FES-cycling solution. *Eur J Transl Myol* 2017;**27**:265–71.
35. Leung KWC, Tong RKY, Wang X, et al. The effectiveness of functional electrical stimulation (FES) in on-off mode for enhancing the cycling performance of team Phoenix at 2016 Cybathlon. *Eur J Transl Myol* 2017;**27**:302–7.
36. Tong RKY, Wang X, Leung KWC, et al. How to prepare a person with complete spinal cord injury to use surface electrodes for FES trike cycling. *IEEE Int Conf Rehabil Robot* 2017;**2017**:801–5.
37. McDaniel J, Lombardo LM, Foglyano KM, Marasco PD, Triolo RJ. Cycle training using implanted neural prostheses: Team Cleveland. *Eur J Transl Myol* 2017;**27**:289–94.
38. Popovic-Maneski L, Aleksic A, Metani A, Bergeron V, Cobeljic R, Popovic DB. Assessment of spasticity by a pendulum test in SCI patients who exercise FES cycling or receive only conventional therapy. *IEEE Trans Neural Syst Rehabil Eng* 2018;**26**:181–7.
39. Arnin J, Yamsa-Ard T, Triponyuwasin P, Wongsawat Y. Development of practical functional electrical stimulation cycling systems based on an electromyography study of the Cybathlon 2016. *Eur J Transl Myol* 2017;**27**:295–301.
40. Wiesener C, Schauer T. The Cybathlon RehaBike: Inertial-sensor-driven functional electrical stimulation cycling by team Hasomed. *IEEE Robot Autom Mag* 2017;**24**:49–57.
41. Bo APL, da Fonseca LO, Guimarães JA, et al. Cycling with spinal cord injury: a novel system for cycling using electrical stimulation for individuals with paraplegia, and preparation for Cybathlon 2016. *IEEE Robot Autom Mag* 2017;**24**:58–65.
42. Wiesener C, Ruppin S, Schauer T. Robust discrimination of flexion and extension phases for mobile functional electrical stimulation (FES) induced cycling in paraplegics. *Int Fed Autom Control (IFAC)-PapersOnLine* 2016;**49**:210–5.
43. Baur K, Haufe FL, Sigrist R, Dorfschmid K, Riener R. The CYBATHLON — bionic Olympics to benchmark assistive technologies. *Inclusive robotics for a better society*. Hoboken, NJ: Springer; 2018.p.175–9.
44. Reinkensmeyer DJ. JNER at 15 years: Analysis of the state of neuroengineering and rehabilitation. *J Neuroeng Rehabil* 2019;**16**:144. doi:10.1186/s12984-019-0610-0.
45. Rabelo M, de Moura Juca RVB, Lima LAO, et al. Overview of FES-assisted cycling approaches and their benefits on functional rehabilitation and muscle atrophy. *Adv Exp Med Biol* 2018;**1088**:561–83.
46. Coste CA, Wolf P. FES-cycling at Cybathlon 2016: Overview on teams and results. *Artif Organs* 2018;**42**:336–41.
47. Schauer T. Sensing motion and muscle activity for feedback control of functional electrical stimulation: Ten years of experience in Berlin. *Annu Rev Control* 2017;**44**:355–74.
48. Szecsi J, Straube A, Fornusek C. Leg general muscle moment and power patterns in able-bodied subjects during recumbent cycle ergometry with ankle immobilization. *Med Eng Phys* 2014;**36**:1421–7.
49. Chou L, Kesar TM, Binder-Macleod SA. Using customized rate-coding and recruitment strategies to maintain forces during repetitive activation of human muscles. *Phys Ther* 2008;**88**:363–75.
50. Aksöz EA, Laubacher M, Binder-Macleod S, Hunt KJ. Effect of stochastic modulation of inter-pulse interval during stimulated isokinetic leg extension. *Eur J Transl Myol* 2016;**26**:229–34.
51. Hunt KJ, Ferrario C, Grant S, McLean AN, Fraser MH, Allan DB. Comparison of stimulation patterns for FES-cycling using measures of oxygen cost and stimulation cost. *Med Eng Phys* 2006;**28**:710–8.
52. Janssen TWJ, Pringle DD. Effects of modified electrical stimulation-induced leg cycle ergometer training for individuals with spinal cord injury. *J Rehabil Res Dev* 2008;**45**:819–30.
53. Graupe D, Suliga P, Prudiant C, Kohn KH. Stochastically-modulated stimulation to slow down muscle fatigue at stimulated sites in paraplegics using functional electrical stimulation for leg extension. *Neurol Res* 2000;**22**:703–4.