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A Review of Assistive Robotic Exoskeletons and Mobility Disorders in Children to Establish Requirements of Such Devices for Paediatric Population

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Abstract: There has been growing interest in robotic exoskeletons over the past two decades, and the use of robotic exoskeletons has increased with the development of technology and wider awareness of their benefits. Although there have been numerous studies in the area of robotic exoskeletons, the research appears to have neglected paediatric population end users. Possible reasons behind this could be the continuous growth of children which affects the requirements of the system and also relatively fewer number of immobilized subjects in the paediatric population compared to adult population. In this paper, firstly a review of state of the art of assistive robotic exoskeletons highlighting the lack of research for paediatric population is presented. Secondly, different mobility disorders in children and system requirements of an assistive robotic exoskeleton for these disorders are addressed.

Keywords: Exoskeleton, Robotics, Children, Mobility Disorders, Cerebral Palsy

1. INTRODUCTION

Robotic exoskeletons are wearable bionic devices which could provide external torque at joints to move that part of body. Robotic exoskeletons are classified into three main groups in terms of the purpose of use: assistive robotic exoskeletons, rehabilitative robotic exoskeletons, and robotic exoskeletons for enhancing physical abilities of healthy subjects [1]. In addition, based on the body part they are used for, robotic exoskeletons are divided into four sub-groups: lower extremity exoskeletons, upper extremity exoskeletons, specific joint support exoskeletons, and full body exoskeletons.

The aims of this paper are reviewing the state of the art by mainly considering assistive lower-body robotic exoskeletons, highlighting the lack of research for paediatric population, identifying different children mobility disorders, and establishing generic and specific system requirements of an assistive robotic exoskeleton for these mobility disorders.

2. STATE OF THE ART

A considerable body of literature has been published regarding robotic exoskeletons for adults. In this section, mainly assistive robotic exoskeletons are presented. As indicated in the previous section, assistive robotic exoskeletons can improve quality of life for paralyzed people by assisting them with Activities of Daily Livings (ADLs), including walking, sitting down, and standing up.

2.1 ReWalk

ReWalk [2, 3] , shown in Fig. 1, is designed by ReWalk Robotics company in the US which is a well-known example of assistive robotic exoskeleton for adults. ReWalk can be used by people with complete Spinal Cord Injury (SCI) for ADLs. There are two different products on the market which are ReWalk Rehabilitation and ReWalk Personal.

Fig. 1. The ReWalk Personal with an immobilized person inside [2].

Assistive robotic exoskeletons are very similar to over ground rehabilitative walking systems, and they can be used for both purposes. Therefore, the design of both ReWalk Rehabilitation and ReWalk Personal exoskeletons are the same. The only difference between ReWalk Rehabilitation and ReWalk Personal is the graphical user interface in the ReWalk Rehabilitation exoskeleton which is used by therapists to change the level of assistance for each individual. In addition, ReWalk Rehabilitation is used as a training equipment before starting the use of ReWalk Personal in the community.

ReWalk has 6 Degrees of Freedom (DOFs) and could provide sagittal plane movements only by active hip and knee joints and passive ankle joint. The exoskeleton is approximately 23 kg and contains a wearable brace that incorporates DC motors at the joints. It has rechargeable batteries which is

carried by the user in a backpack as well as the computer-based controller.

ReWalk has four action modes: sit to stand, stand to sit, up steps, and down steps. Tilt sensors are used to determine the movements of upper-body, the signal from tilt sensors is considered as the intention of the lower-body movement. As a safety feature the quick flexion of hip and knee joints are prevented which might cause a fall. In addition, in case of a power failure, the exoskeleton collapses gently.

ReWalk was accepted by the U.S. Food and Drug Administration (FDA) in 2014 as a personal device and can be used by SCI patients. Although it is one of the best exoskeleton in the market based on clinical study results [4], one important challenge associated with this exoskeleton is that there is no self-balance control. Therefore, crutches are always needed.

2.2 Vanderbilt – Indego

The Vanderbilt exoskeleton [5-8], shown in Fig. 2 (a), was developed by Vanderbilt University for paralyzed people to help them to accomplish some daily activities including walking, sitting, and climbing stairs. Although the exoskeleton was designed by Vanderbilt University, the commercialization of it was made by Parker Hannifin Corporation according to an exclusive agreement between them in October 2012 [9]. After this agreement, the Vanderbilt exoskeleton was named as Indego and was commercialized in 2015 as two different products: Indego Personal and Indego Therapy as depicted in Fig. 2 (b).

Fig. 2. The Vanderbilt exoskeleton, (a) the prototype of Vanderbilt exoskeleton by Farris et al. [33], (b) the commercialized Indego exoskeleton by Parker Hannifin Corporation [9].

The Vanderbilt – Indego exoskeleton has no support between the ankle joint and foot. Therefore, an additional support is needed as it is included in Fig. 2 (b) for just demonstration purpose. Hip and knee joints are actuated in the sagittal plane only by two brushless DC motors. The total weight of the exoskeleton is 12 kg, which is comparatively lightweight in the class of assistive robotic exoskeletons. In addition, the average speed of the exoskeleton is 0.8 km/h, which is a reasonable speed compared to other available robotic exoskeletons in the area.

The Vanderbilt – Indego exoskeleton has a unique design. As it is clear from Fig. 2, the exoskeleton does not contain a backpack for the battery while the battery is placed around the waist line. It is a modular exoskeleton and could be divided into five parts: a hip segment, two thigh and shank segments, which makes the exoskeleton easily wearable. In addition, all segments have three different sizes to meet different patients' anthropometry.

The Vanderbilt – Indego exoskeleton works in combination of Functional Electrical Stimulation (FES) to contract and relax the paralyzed muscles of the user. The idea is to combine metabolic and robotic power sources while obtaining both the physiological advantages of FES and the control advantages of the assistive robotic exoskeleton. Therefore, the control structure includes two different control loops: a motor control loop and a muscle control loop. In addition, Indego involves a fall detection system. In case of any fall, the exoskeleton makes quick adjustments to user's position to minimize any risk of injury while in case of any power failure, knee joints are locked and hips joints are free.

The Vanderbilt – Indego exoskeleton has two working modes: standby mode, which allows the user to stop between modes, and go mode. To begin walking and transit from sitting to standing, the user should tilt forward until feeling a vibration in the waist. In addition, the level of assistance of both the therapeutic and the personal exoskeletons can be adjusted to give more independence and control to the users where the level of disability is changing from one user to another.

One preliminary assessment of the exoskeleton was completed by the development team [5] with a T10 motor and sensory complete injured subject and results show that there was a significant enhancement in walking speed while a considerable reduction was seen in the metabolic energy consumption. After all assessments [5, 7, 8], in March 2016, Indego exoskeletons were approved by the U.S. FDA for the use with spinal cord injuries either in a clinical environment or personal environment.

In terms of limitations, one major drawback of this exoskeleton is the battery life, which is up to 4 hours continuous power. A further difficulty arises, however, when an attempt is made to support a person weighed more than 91 kg. In addition, a pair of crutches is still needed to provide balance control. Therefore, the use of the Vanderbilt – Indego exoskeleton is limited by three significant factors which are power consumption, the weight of the user, and balance control.

2.3 REX

REX [10, 11] is designed and manufactured by REX Bionics Ltd in New Zealand, presented in Fig. 3. The development process started in 2003, and the first prototype was introduced in 2007. REX can be used by subjects with many different mobility disorders, such as different levels of SCI. There are currently two different products available: REX P, which is intended to be used as a personal device for ADLs, and REX Rehab, that is used in clinical environments to perform some exercises by patients under the supervision of therapists.

Fig. 3. REX with a spinal cord injured subject in it [11].

The mechanical structure of REX includes two tethered legs, an upper-body support as well as an abdominal support. The exoskeleton has 10 DOFs driven by electric motors while the supported movements are flexion/extension and abduction/adduction at hip joints, flexion/extension at knee joints, and at the ankle joints dorsiflexion/plantarflexion and eversion/inversion. The length of each part is also quickly and easily adjustable for different subjects' anthropometry. In addition, the exoskeleton comes with two rechargeable and exchangeable batteries where each battery last for only one hour which makes two hours continuous power. Although the battery life is short, the exoskeleton does not require any power while standing.

REX is controlled by a joystick and can be used by many different injuries, as stated previously. However, the main condition for the user is to be able to use the joystick. In other words, REX is only suitable for manual wheelchair users who have the control of their upper-body. Besides this minor condition, the exoskeleton could only be used by users who weigh up to 100 kg, which is an important limitation of the exoskeleton. In contrast to these limitations, REX does not require any additional support for balance control that makes REX the first and only lower extremity exoskeleton which does not necessitate any stability support.

REX is one of the heaviest and bulkiest exoskeletons, approximately 48 kg, in the class of assistive robotic exoskeletons because of its unique frame design where it is a mobility assistance platform rather than a walking device. As it is clear from Fig. 3 the user stands on the footplates, and the exoskeleton walks on behalf of the user where the user makes minimal effort. The user can walk, sit, stand, turn, and navigate stairs and slopes with the help of REX. In addition, it is the only exoskeleton which can go backward. However, the speed of gait and its large mass are major limitations of this exoskeleton.

The evaluation of REX in terms of safety and feasibility is still ongoing internationally in the UK, New Zealand, and Australia. The initial part of the trial was named as RAPPER [12] and involves 56 subjects with SCI. The results of this study show that approximately 90% of the participants were able to complete the trial and walk with REX without any serious problem. The second part of the trial was named as RAPPER II, and the interim results are presented by Birch et al. [13]. This part involves 20 participants: 15 subjects with paraplegia between the levels of T1 to L5 and 5 subjects with tetraplegia between the levels of C4 and C8. The results indicate that REX is harmless and practicable to assist patients either for ADLs or in rehabilitation sessions. It is also important to note that REX currently has CE marking and available in CE Mark recognized countries, such as the UK and Europe. However, it is not available in the US since it has not been approved by the U.S. FDA yet.

2.4 MindWalker

MindWalker [14, 15] is a research prototype developed by University of Twente, Netherlands in 2012. It is a lower extremity exoskeleton, as indicated in Fig. 4 and intended to be used by subjects with paraplegia who weigh up to 100 kg. The aim of the research was to combine the following three areas in one exoskeleton: Brain Machine Interface (BCI) technology, Virtual Reality (VR), and exoskeleton mechatronics and control.

Fig. 4. MindWalker exoskeleton [16].

MindWalker has 6 activate DOFs, powered by series elastic actuators, and 4 passive DOFs assisted by springs, 10 DOFs in total. Actuated movements are abduction/adduction and flexion/extension at hip joints, flexion/extension at knee joints while passive movements are plantarflexion/dorsiflexion at ankle joints and internal/external rotations at hip joints. The weight of the exoskeleton is 28 kg excluding batteries, and its maximum speed is 0.8 m/s. The displacement of centre of mass stimulates the finite state-based controller to initiate movements. In addition, a pushbutton is used to start and stop the walking of the exoskeleton.

The preliminary evaluation results show that healthy subjects are able to walk without any additional balance support device while paraplegic subjects are not able to walk without crutches [16], where the main aim of the project was to provide walking without crutches. Therefore, the exoskeleton is still under development and evaluation process.

2.5 EksoGT

EksoGT [17] is designed by the Ekso Bionics Company in the US. EksoGT was initially intended for military use. However, it was later converted for use as a rehabilitative exoskeleton, but it is an over ground walking system as it is clear from Fig. 5. Additionally, it could be used as an assistive robotic exoskeleton. The exoskeleton consists of

two aluminium legs, a battery, and a backrest to attach different kind of loads.

Fig. 5. EksoGT exoskeleton with a patient inside [17].

EksoGT was designed to be adaptable to a wide range of patients, including paralyzed and post stroke patients. Therefore, the degree of assistance provided by the exoskeleton can be adjusted to meet each patient's unique needs. It weighs approximately 20 kg and can achieve a maximum speed of 0.8 m/s. The exoskeleton has 6 DOFs, but only provides movements in the sagittal plane. Its hip and knee joints are actuated, while the ankle joint is sprung and passive. EksoGT has four use modes: therapist actuates steps by using a button, user actuates steps by using a button, user achieves the next step by moving the hips laterally, and steps that are done by the intention of the user. In addition, as a unique feature, the actuators could be controlled individually.

The length of each part is adjustable to adapt patient whom height is ranging from 158 to 195 cm. The use of EksoGT has the advantages of high manoeuvrability, strength of the structure, and its ergonomics while one of the main limitation is that it is only suitable for patients weighing maximum 100 kg. Furthermore, the battery life of the EksoGT is 6 hours for a single charge, and in the event of power failure, knees are locked and hips are free to protect the patient from fall.

In 2016, EksoGT was approved by the U.S. FDA for treating SCI levels to C7 and stroke patient, which makes it first approved robotic exoskeleton for the use of stroke patients. EksoGT is verified by the worldwide clinical studies which confirm that EksoGT has significant impact on the regaining the abilities of correct gait pattern [18] while there is still no major improvement in the step and stride length and cadence. It is still under development, with the aims of reducing its weight and improving the adaptability to different patients.

2.6 HAL

The Hybrid Assistive Limb (HAL) [19] is one of the most enthusiastic robotic exoskeleton covered in this paper. It is developed by the University of Tsukuba in Tsukuba, Japan, and cybernics technology is used in this exoskeleton, which makes HAL a unique design. Cybernics technology is a multidisciplinary area which combines neuroscience, mechatronics, and information technologies. In other words, brain signals are used in the control loop to determine the intention to move any limb.

There are currently four different versions of HAL exoskeleton: a full-body version, a lower-body version, a single-leg version, and a single-joint version. HAL is of interest because it is the only full-body robotic exoskeleton that is currently on the market. In addition, HAL can be used for different purposes such as an assistive product or therapeutic product or a human performance enhancement product.

The assistive device, HAL-1 [19], is the first developed prototype of HAL in 1999, which is only a lower-body exoskeleton, and shown in Fig. 6 (a). The focus was on assisting immobilized subjects to perform ADLs. The mechanical structure consists of 4 DOFs, and flexion/extension movements at both hip and knee joints are actuated by DC servo motors. As a second version of this exoskeleton, HAL-3 [20] was designed between 1999 and 2003, which is depicted in Fig. 6 (b). The structure is the same as the previous version, HAL-1, and has 4 DOFs. This lower-body type exoskeleton weighs 15 kg while the frame is made of aluminium alloy and steel. Compared to HAL-1, HAL-3 is more suitable for daily use [19].

Fig. 6. HAL robotic exoskeleton, (a) the first prototype HAL-1, and (b) the second product HAL-3 [19].

The assistive HAL has been improved since then, and it is currently in a more modern structure. In Fig. 7, both the two-leg version (a) and the single-leg version (b) of modern HAL are shown. It is currently commercialized with the name of 'HAL for Living Support' [21]. The actuated joints are the same as with the previous version where there are 2 active DOFs at each leg.

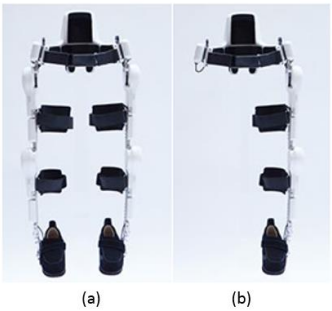

Fig. 7. Modern HAL for Living Support, (a) the two-leg version, (b) the single-leg version [21].

There are currently 3 different sizes available: Small (S) size is for users between 145 cm and 165 cm height while Medium (M) size is for users between 150 cm to 170 cm height, and Large (L) size is for the users between 165 cm to 185 cm. In addition, both the upper-leg and the lower-leg

lengths are adjustable with a number of notches where there is 1.5 cm gap between each of them. The double-leg version is approximately 12 kg, excluding the lithium polymer battery, while the single-leg version is 7 kg. The battery can provide between 60 minutes to 90 minutes continuous power. Besides having relatively short battery life, a further key limitations of this device is that the use of it is limited by the weight of the user, maximum 80 kg, which is quite low when considering the increasing weight of population across the world [22].

In terms of therapeutic device, HAL-Medical [23] is designed. The mechanical structure is exactly the same as the assistive device. The control algorithm for this device is designed to teach the brain how to walk. HAL-Medical is currently on the market in Japan and Europe. In addition, it is the only therapeutic device that has been approved by CE Marking (CE 0197). The feasibility of HAL-Medical is reported by Grasmucke et al. [24] after 4 years of using the device with 20 acute and 40 chronic SCI subjects. This study also indicates the safeness of HAL-Medical for the use with acute and chronic SCI patients without any problem. The feasibility and suitability of HAL-Medical is also verified by Cruciger et al. [25] and Fujii et al. [26].

2.7 Exoskeletons specifically for children

The research on robotic exoskeletons to date has tended to focus on adults rather than children. Therefore, the existing literature on neither assistive robotic exoskeleton nor therapeutic robotic exoskeleton for children are insufficient. One possible reason of this could be the continuous growth of children which continuously affects the requirements of the system.

2.7.1 ATLAS

A preliminary concept of lower limb robotic exoskeleton for children is ATLAS [27]. ATLAS was specially designed to assist sagittal plane movements of a girl with quadriplegia who could not move any of her limbs. This was a system with 6 DOFs while only the hip and knee joints were powered. It was designed to be portable, lightweight (6.5 kg), comfortable and safe for providing gait assistance. This proposed approach was experimentally validated. However, the challenges that are associated with this design are power supply, which needs to be portable and have long life, being lightweight, and powerful actuator.

A second part of ATLAS project has been done which is ATLAS 2020 [28, 29] and was not designed for only a specific user. It is an easily adaptable exoskeleton for children between 3 to 14 ages to provide them 3D walking with 10 DOFs. Although it is not displayed in Fig. 8, there is an auxiliary frame attached to the exoskeleton for balance control. In addition, the exoskeleton is 14 kg which is a further significant limitation of ATLAS 2020.

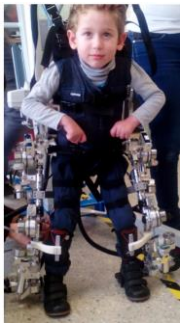

Fig. 8. ATLAS 2020, worn by a disable user [28].

As mentioned above, ATLAS 2020 does not have self-balance control. Therefore, a further version, ATLAS 2030 [30], was develop with self-balance control by removing the frame. It has the same specifications with ATLAS 2020 such as providing 3D walking with 10 DOFs and targeting children from 3 to 14 years old. Nevertheless, ATLAS 2030 is still 14 kg which is an enormous weight for a 3 years old child.

2.7.2. WAKE-up

Wearable Ankle Knee Exoskeleton (WAKE-up) [31, 32] is a further multi-joint lower limb exoskeleton designed for rehabilitation of children with neuromuscular diseases. WAKE-up is not a full lower-body exoskeleton, as indicated in Fig. 9 (Appendix A). It is a modular exoskeleton involving two separate joint modules: a knee joint module and an ankle joint module. In Fig. 9 the detailed illustration of joint modules are indicated. Each module has 1 DOF that makes the two-leg version of WAKE-up 4 DOFs. The weight of each module is 2.5 kg, and Rotary Series Elastic Actuators (RSEAs) is used to enhance the safety of users.

Fig. 9. The details of the WAKE-up system with joint modules and shoe pad [32].

The WAKE-up could assist sagittal plane movements only, and the target age group is from 5 years old to 13 years old children with neuromuscular disease such as Cerebral Palsy (CP). The exoskeleton was tested with four healthy children and three children with CP by the same research team. The results show that the exoskeleton has positive impact on physical gait patterns. However, as it was mentioned by the authors as well, the robustness of the system is needed to be improved.

2.7.3 An Active Exoskeleton Designed by Lerner et al. [33]

A recent study by Lerner et al. [33] describes the design of an active single-joint robotic exoskeleton for children with CP. The aim of the presented system is to assist knee extension to address crouch gait in children. The exoskeleton was designed as a knee-ankle-foot orthosis system. Consequently, this design cannot be classified as a full lower-body exoskeleton.

The mechanical structure of the exoskeleton, as presented by Lerner et al. [33], is based on a modular approach, and its total weight is 3.2 kg. The exoskeleton consists of 1 DOF for per leg at the knee joint, and brushless DC motors are used as actuators to provide adequate assistance for the knee extension.

The clinical trial [33] proved that the exoskeleton reduces the level of crouch in children with CP. However, some limitations were associated with this exoskeleton. One source of weakness identified in the study was the lack of participants in the experimental process which involved just one applicant. Secondly, a separate 1.96 kg control box was not carried by the participant during the experiment. Finally, during the clinical trial, the exoskeleton was powered by a tethered supply although the battery should be carried by the user in practice. If both the control box and the battery are carried by the user, the total weight of the exoskeleton would increase; thus, this affects the inertia of the movements. In addition, weight is one of the major challenges associated with all robotic exoskeletons.

2.7.4 CPWalker

In Fig. 10 the concept of CPWalker [34] is shown which is a treadmill-based rehabilitative robotic exoskeleton designed to rehabilitate children with CP. CPWalker includes two main components: smart walker part and exoskeleton part. The smart walker part could provide balance control with dynamic weight support while the exoskeleton part helps patients to move their limbs. All three joints, hip, knee, and ankle joints, are actuated with brushless DC motors. The system is still under development to be adaptable with different disorders from CP.

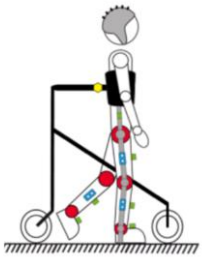

Fig. 10. The concept of CPWalker exoskeleton system [34].

2.8 Summary

The reviewed literature revealed remarkable improvements in general in robotic exoskeletons. Although, the majority of the available research focused on developing systems for adults, some preliminary models of exoskeletons have been designed for children with their special needs, in the past few years.

In Appendix A, a summary of specifications of reviewed exoskeletons is provided. As it is clear, most of them require to use of crutches for balance control. However, there is no way to use crutches or any other additional device to assist fully paralyzed patients. Therefore, providing self-balance control is vital in the matter of addressing a larger community of immobilized population. A further important point is that increasing the number DOF is needed in terms of providing more natural-like human movements. However, increasing the DOF can also lead to high energy consumption which is a further key issue for the robotic exoskeletons.

One of the significant limitation that associated with all types of robotic exoskeletons is the safeness of the system [35-40]. Therefore, the U.S. FDA announced that all active robotic exoskeletons are classified as Class II medical devices which contain moderate to high risk factor because of risk of fall, sudden blood pressure changes, premature battery failures, skin abrasions, and electric shocks [38]. Besides the safety issues, there are still many other challenges associated with all types of exoskeleton, such as the mechanical design of the exoskeleton, actuators, heavy equipment, noise in use, energy efficiency issues, the human – exoskeleton interface, and cost.

Any further development of robotic exoskeleton in the future seems to be in two new directions: soft robotics and modular robotics [38]. Soft robotics is an innovative way of designing lightweight robotic exoskeletons by reducing the total weight. In addition, soft robotic exoskeletons could be used for patients who have difficulties to fit into the current rigid exoskeletons because of their unusual body posture. On the other hand, modular robotic exoskeletons could be specifically used for the support of single joints where needed. In addition, it could make the exoskeleton easily wearable by dividing the exoskeleton into modular parts.

3. DISORDERS AFFECTING CHILDREN

Movement disorders could be defined as neurologic syndromes, which can lead to either excess of movement or lack of movement [41]. Movement disorders are broadly classified into two main groups: hypokinetic movement disorder, which is lack of movement, and hyperkinetic movement disorder, which is excess of movement [42]. Hypokinetic movement disorders include Parkinsonism, apraxia, bradykinesia, and hesitant gait while hyperkinetic movement disorders involve tremor, dystonia, chorea, and tics.

In the paediatric population hyperkinetic movement disorders are more common than hypokinetic movement disorders [42], which mainly result in immobilization. This might be one of the reason behind why there is lack of research in robotic exoskeletons for children and why children are neglected in this area. Although mobility disorders are relatively rare in paediatric population, there is a considerable number of children have difficulties with mobility. In this section, some

disease and disorders are presented which could lead to child immobilization.

3.1 Cerebral Palsy

Cerebral Palsy (CP) is one of the most common and severe physical disorder with the prevalence of 2.5 per 1000 children in developed countries [43], and its prevalence rate has not changed for last 60 years [44]. The term of CP is used to describe a wide group of permanent disorders including developmental disorders and movement disorders. CP is basically the result of abnormalities in the brain. The signs and symptoms can be seen from the beginning of pregnancy or any time in the early childhood.

Children with CP usually have motor disorder, such as difficulties in performing basic ADLs, rather than learning disorders, but sometimes some learning difficulties may be seen depending on the severity of CP level [43]. Currently, there is no cure for CP. However, some assistive devices, such as robotic exoskeletons or standing frames could be used to improve the quality of life of individuals with CP [44].

The classification of CP can be made in three different ways: based on motor-type, topography, or gross motor function of the disorder [45]. Motor-type and topography based classifications are traditional classification systems, and the definition of an individual's disability could be in both of this classes because of their very generalized borders [43]. Therefore, as a reliable classification method gross motor function classification system is preferred by experts.

Motor-type classification system consists of four sub-groups: spasticity, dyskinesia, ataxia, and hypotonia [43]. Spasticity is the most common type of CP, and it is the term used to describe the circumstances when muscles are overactive. This could result in gait disturbances, pain, and muscle weakness. Dyskinesia involves involuntary and uncontrolled muscle movements while ataxia leads to balance and coordination problems and locomotion difficulties. Finally, hypotonia occurs when there is decreased muscle tone, and this is the least common type of CP. In addition, it is also reported that 30% of individuals with CP are classified into more than one group [46]. This shows that motor-type classification system is a poor system in terms of reliability.

Topography based classification system has three categories: hemiplegia, diplegia, and quadriplegia (tetraplegia) [43]. Hemiplegia is the paralysis of one side of the body, and upper-body extremities are more affected than lower-body extremities. In diplegia, both lower-body extremities are more severely affected than upper-body extremities. Finally, quadriplegia (tetraplegia) is the case when all limbs are paralysis. As it is very clear, this classification system is also very generalized and could not meet with needs.

Finally, based on gross motor function classification system CP is divided into five different level in terms of the severity of disorder [43]. Individuals in Level I can sit and walk without any assistance while subjects in Level II walk with assistive devices and sit with some minor balance problems. Level III subjects can only walk short distances indoors with assistance. In contrast, Level IV subjects can only creep instead of walking for short distances and can sit when they are placed. Finally, Level V subjects cannot even sit or walk independently.

3.2 Spinal Muscular Atrophy

Spinal Muscular Atrophy (SMA) is a relatively rare but a progressive genetic disease with the prevalence of approximately 1 in 6000 people [47]. In contrast, the carrier frequency of SMA is high which is 1 in 50 people [48]. It is a severe genetic disease mainly affecting children and leading to child mortality and immobilization across the world [49]. Basically, it is the result of a mutation occurs in survival motor neuron 1 (SMN1) gene, which is the gene responsible for producing protein for motor neurons [50]. When there is a disruption in production of protein in SMN1 gene, survival motor neuron 2 (SMN2) gene is activated to compensate the lack of protein in motor neurons [51]. However, SMN2 gene could only provide a small amount of protein, which is not able to completely compensate the need. Therefore, as a result of protein shortage, muscle weakness occurs, mainly in muscles used for ADLs, and severity of the muscle weakness addresses the type of SMA [52].

SMA can be classified into four main types based on the severity of the disease: Type I, Type II, Type III, and Type IV [48, 53]. According to Ogino et al. [54], 58% of all subjects with SMA diagnosed as Type I SMA while 29% is Type II SMA, and 13% is Type III SMA. Although SMA is principally categorized into four main groups, each subject with SMA has a unique progression, and it is difficult to classify. Distinguishing symptoms are progressive loss of independency and immobilization.

Firstly, Type I SMA, which is also named as Werdnig-Hoffman disease [53], is the most severe form of SMA. The symptoms of Type I SMA could be seen at birth or within a few months after birth. Subjects with Type I SMA can never be able to sit unassisted or support their head. In addition, breathing problems could also be seen. The life expectancy for Type I SMA patients is less than 2 years. Secondly, Type II SMA is developed between 6 and 12 months after birth, and subjects could live into adulthood [48]. The maximum independency of subjects is being able to sit without support. However, these subjects can never stand or walk independently.

Type III SMA is a milder version of the disease, which is also named as Kugelberg-Welander disease [53]. This type of SMA could be developed from early childhood to adolescence, and subjects could survive into adulthood. Subjects with Type III SMA could stand and walk independently in the early period of diagnosis, which is the difference between Type II SMA and Type III SMA. However, approximately half of all individuals with Type III SMA lose their ability to walk by age 14 [48] because as mentioned earlier, SMA is a progressive disease. Finally, Type IV SMA is the mildest type of SMA and can occur after

age 30 [53]. Subjects could experience mild muscle weakness mostly in their upper arms and legs. Individuals with Type IV SMA could stand and walk independently. However, they might lose this ability later.

In terms of treatment of SMA, the Spinraza drug is the only available drug for the treatment [55]. The U.S. FDA approved Spinraza at the end of 2016 [56]. The effectiveness of this drug is under the evaluation process, and preliminary tests on mice are promising [52, 57-59]. However, the result of using this drug is just minimizing the effects of SMA rather than providing complete cure for it.

3.3 Spinal Cord Injury

Spinal Cord Injury (SCI) is the result of any damage to the spinal cord which blocks or disrupt the communication between brain and body [60]. SCI affects sensory and motor functions, and it is classified in two different ways: paraplegia/tetraplegia or complete/incomplete [61]. Firstly, paraplegia is the paralysis of lower-body while tetraplegia is the complete or partial loss of upper and lower-body functions. Secondly, complete SCI means that all functions below the injured nerves are stopped which leads to paralysis of the body below that point while incomplete SCI refers to that some functions and sensations below the injured nerves are still functioning.

The causes of SCI could be addressed in two groups: traumatic injuries and non-traumatic injuries [62]. Traumatic causes are motor vehicle accidents, falls, and sportive activities while non-traumatic causes are based on illness, such as cancer, osteoporosis, inflammation of spinal cord, arthritis, and sclerosis. Universally, motor vehicle accidents and falls are the most common causes of SCI between these causes [60, 63, 64]. For instance, the rate of motor vehicle related SCI is approximately 55% of all paediatric SCI in the US [63].

Before the injury levels are described, it is important to mention the basic anatomy of spinal cord. Spinal cord is covered with ring shaped bones named vertebrae, and vertebrae are divided into five main regions: cervical (C1 – C8), thoracic (T1 – T12), lumbar (L1 – L5), sacral (S1 – S5), and coccyx nerves [62]. Cervical nerves are located on neck area while thoracic, lumbar, sacral, and coccyx nerves are respectively located on chest, low back, pelvis, and tail bone areas. The severity of SCI depends on the place of the damage occurred on vertebrae regions, and it decreases from cervical nerves to coccyx nerves.

The most severe form of SCI is the result of any damage that occurred on the high-cervical nerves (C1 – C4) [62]. Subjects within this level of injury become fully paralyzed and lose the control of upper and lower extremities. In addition, they might have difficulties in breathing and control of bowel movements. In contrast, any damage to low-cervical nerves (C5 – C8) can lead to the paralysis mainly in lower extremities, and individuals might be able to breath and speak. Secondly, thoracic nerves damages (T1 – T12) mainly affect chest, mid-back, and abdominal muscles. Patients with this level of injury might stand in a standing frame while they still use their upper-body extremities as usual. Finally, lumbar nerves damages (L1 – L5) can cause functional impairment in the hip and legs while sacral nerves damages (S1 – S5) could lead to temporary loss of some lower-body functions.

The certain number of people suffered from SCI is not known. However, according to World Health Organization (WHO) [65], the annual incidence rate of SCI is between 250 000 to 500 000, and the paediatric SCI population constitutes 6 – 10% of it [64, 66]. The injury level in the paediatric population is usually high-cervical nerves damages, which is the most severe form of SCI. Paediatric SCI is different from adult SCI in terms of a higher potential recovery chance and the mechanism of injury while each subject has a unique form of disability [66]. Therefore, providing rehabilitative or assistive robotic exoskeletons for these subject could increase their chance to recover.

3.4 Stroke

A further rare, but, serious disease that affects children and leads to immobilization and mortality is paediatric stroke. Basically, stroke is the result of blockage or breakage of blood vessel in the brain which lead to permanent or temporary brain damage [67, 68]. There are two main sub-groups of stroke: ischemic stroke, which occurs when there is a blockage of blood vessels, and haemorrhagic stroke, which occurs when there is a breakage of blood vessel [69]. Ischemic stroke is also divided into two sub-groups: arterial ischemic stroke and cerebral venous sinus thrombosis. Arterial ischemic stroke occurs when the blockage occurs in an artery vessel while cerebral venous sinus thrombosis occurs as a result of blockage in a vein vessel [67].

In the paediatric population, approximately half of all stroke cases is arterial ischemic stroke [70], that makes it the most common type of paediatric stroke. The incidence of arterial ischemic stroke is between 2 to 3 cases per 100,000 cases each year for subjects younger than 5 years of age while it is between 8 to 13 cases per 100,000 cases each year for subjects from 5 to 14 years of age [71].

The causes and risk factors of paediatric stroke might be cardiac diseases, infections, hematologic disease, trauma, drugs, and syndromic and metabolic disorders [69]. In terms of paediatric stroke, cardiac diseases are the most common source of stroke with the rate of 33% of all arterial ischemic stroke [72]. Sickle sick disease is a further common source of paediatric stroke with the rate of 285 cases per 100,000 cases [73].

The symptoms of stroke in young children are different from adults which might lead to misdiagnosis [74]. For instance, the symptoms of stroke in a toddler could be continuous crying, feeding difficulties, and sleepiness while speaking difficulties, vision abnormalities, dizziness, balance and walking problems, and weakness of one side of body could be seen as the symptoms of stroke in adults. The symptoms

of stroke are more adult-like as the subject's age increases [69].

After sustaining stroke, some temporary and some permanent impairments could be seen including speech and language disorders, epilepsy, cognitive and behavioural impairments, and psychologic complications and more importantly hemiparesis and movement disorders, which cause immobilization of subject [69]. Hemiparesis, which is permanent weakness of one side of body, is the most common outcome of stroke [73-75].

3.5 Spina Bifida

Spina bifida is a type of neural tube defect [76]. It occurs when the neural tube cannot complete its development during early weeks of pregnancy and still open after birth. Babies with spina bifida often have a sac on their back to cover the gap, which is a skin with a fluid inside. Spina bifida is the most common type of neural tube defect with a rate of 1 in 2500 new-borns worldwide [76]. The cause of spina bifida is still unknown. However, lack of folic acid during the pregnancy seems a significant source of spina bifida [77].

There are mainly three types of spina bifida: myelomeningocele, meningocele, and spina bifida occulta [77]. Firstly, myelomeningocele is the most common form of spina bifida in which the subject's spinal canal is still open along many vertebrae. In this form of spina bifida, spinal cord and protective membranes can be pushed out from the sac on the back of subject. Secondly, meningocele is also a severe form of spina bifida. The difference between myelomeningocele and meningocele is that in meningocele type of spina bifida only spinal cord is pushed out, and with a surgery this could be solved with a minimum damage to the nerves. Finally, spina bifida occulta is the mildest form of spina bifida. However, it is the most common form of it. In this form of spina bifida, only a few vertebrae are not developed properly, and a small gap occurs in the spine. This type of spina bifida does not lead to any problem, and many subjects with it live without knowing it.

In terms of treatment, although surgery could be a solution to close the gap in the spine and give subject chance to live into adulthood, the damage made in the nervous system cannot be restored [77]. Therefore, some permanent problems occur, including weakness or paralysis of legs and loss of skin sensation in the lower-body. In this case, rehabilitation therapies and assistive robotic exoskeletons are crucial elements in terms of improving the independence of subject.

4. GENERIC AND SPECIFIC SYSTEM REQUIREMENTS OF AN ASSISTIVE ROBOTIC EXOSKELETON FOR CHILDREN

In this section, some generic and some specific system requirements of an assistive robotic exoskeleton for children who have any of the disabilities described above are presented. First of all, it is important to know the maximum level of independency of individual at each level of disabilities although it is difficult to generalize disabilities where each subject has her/his own unique disability. In Appendix B the maximum level of independency for different levels of each disorder is addressed, which have already been mentioned in the previous section. By considering this table Level I CP, Type IV SMA, and spina bifida occulta are out of scope because Level I CP and spina bifida occulta subjects are still able to stand and walk without any assistance, and Type IV SMA occurs after 30 years of age.

In terms of generic design aspects for an assistive robotic exoskeleton, it is crucial to primarily consider the comfort and safety of users for all different level of disabilities. Secondly, the mechanical structure of the exoskeleton should be light weight because the mass of the exoskeleton affects the inertia of user's joints [37]. Furthermore, the exoskeleton should be able to provide full range of motion as a healthy subject could have, which is also related to the comfort of the user.

In terms of specific design aspects, one of the most important issues is the balance control of the exoskeleton by considering the abilities of subjects from different type and level of disorder. The balance control of an assistive robotic exoskeleton could be done in two different ways either with the use of crutches/standing frames or providing self-balance control. Use of additional assistive tools for balance control requires full upper-body functioning of the user. Therefore, it is necessary to provide self-balance control for subjects with upper extremity disorders, such as subjects with high-cervical nerves damages. Moreover, a modular design approach could be beneficial for subjects who have partial body impairments, such as post-stroke patients. Modular design could also affect the comfort of the use by decreasing the time spent on wearing the exoskeleton.

5. CONCLUSION

Previous design and developments in robotic exoskeletons are presented in this paper, and there is no doubt that the research which has been carried out specifically for paediatric population is insufficient. As stated previously, there might be two main reasons behind this circumstance: continuous growth of children and comparatively fewer number of children with ambulation disorders. However, although it is comparatively lower, the number of children with mobility disorders is certainly unneglectable. Therefore, different mobility disorders are addressed which mainly affects children, such as CP, SMA, and spina bifida. Then, generic and specific system requirements of an assistive robotic exoskeleton are established. One key issue with establishing system requirements is that each individual has a unique disability, and it is difficult to generalize the requirements. However, at very basic level, generic system requirements could be listed as comfort and safety of users, range of motion, and system weight while balance control of the system should be considered as a specific requirement for each individual.

REFERENCES

1. Chen, B., et al., Recent developments and challenges of lower extremity exoskeletons. Journal of Orthopaedic Translation, 2016. 5: p. 26-37.
2. Esquenazi, A., et al., The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. American Journal of Physical Medicine & Rehabilitation, 2012. 91(11): p. 911-921.
3. Talaty, M., et al. Differentiating ability in users of the ReWalk (TM) powered exoskeleton an analysis of walking kinematics. in 13th IEEE International Conference on Rehabilitation Robotics (ICORR). 2013. Univ Washington Campus, Seattle, WA: Ieee.
4. Raab, K., et al., Effects of training with the ReWalk exoskeleton on quality of life in incomplete spinal cord injury: a single case study. Spinal Cord Series and Cases, 2016. 2: p. 15025.
5. Farris, R.J., et al., A Preliminary assessment of legged Mobility provided by a lower limb exoskeleton for persons with paraplegia. Ieee Transactions on Neural Systems and Rehabilitation Engineering, 2014. 22(3): p. 482-490.
6. Farris, R.J., et al. Design of a joint-coupled orthosis for FES-aided gait. in 2009 IEEE International Conference on Rehabilitation Robotics. 2009.
7. Murray, S.A., et al., An assistive control approach for a lower-limb exoskeleton to facilitate recovery of walking following stroke. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2015. 23(3): p. 441-449.
8. Ha, K.H., S.A. Murray, and M. Goldfarb, An approach for the cooperative control of FES with a powered exoskeleton during level walking for persons with paraplegia. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2016. 24(4): p. 455-466.
9. Indego. *Powering People Forward*. [Online]. [Accessed 22 December 2017]. Available from: http://www.indego.com/indego/en/home.
10. Lajeunesse, V., et al., Exoskeletons' design and usefulness evidence according to a systematic review of lower limb exoskeletons used for functional mobility by people with spinal cord injury. Disability and Rehabilitation: Assistive Technology, 2016. 11(7): p. 535-547.
11. REX Bionics. *Robot for Rehabilitation: Exercising, Walking and Standing*. [Online]. [Accessed 30 December 2017]. Available from: https://www.rexbionics.com.
12. Clinical Trials. *Safety and Feasibility Evaluation of Robot Assisted Physiotherapy Exercises with REX (SAFE RAPPER).* [Online]. [Accessed 30 December 2017]. Available from: https://clinicaltrials.gov/ct2/show/NCT02417532.
13. Birch, N., et al., Results of the first interim analysis of the RAPPER II trial in patients with spinal cord injury: ambulation and functional exercise programs in the REX powered walking aid. Journal of Neuroengineering and Rehabilitation, 2017. 14: p. 10.
14. Gancet, J., et al. MINDWALKER: going one step further with assistive lower limbs exoskeleton for SCI condition subjects. in 4th IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob) / Symposium on Surgical Robotics. 2012. Rome, ITALY: IEEE.
15. Wang, L., et al. Actively controlled lateral gait assistance in a lower limb exoskeleton. in 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. 2013.
16. Sylos-Labini, F., et al., EMG patterns during assisted walking in the exoskeleton. Frontiers in Human Neuroscience, 2014. 8(423).
17. Ekso Bionics. *EksoGT*. [Online]. [Accessed 22 November 2017]. Available from: http://eksobionics.com/eksohealth/products/.
18. Nooijen, C.F.J., N. ter Hoeve, and E.C. Field-Fote, Gait quality is improved by locomotor training in individuals with SCI regardless of training approach. Journal of Neuroengineering and Rehabilitation, 2009. 6: p. 11.
19. Sankai, Y., HAL: Hybrid Assistive Limb Based on Cybernics. Robotics research, 2010. 66: p. 25-34.
20. Kawamoto, H., et al., Power assist method for HAL-3 using EMG-based feedback controller, in 2003 Ieee International Conference on Systems, Man and Cybernetics, Vols 1-5, Conference Proceedings. 2003, Ieee: New York. p. 1648-1653.
21. Cyberdyne. *HAL for Living Support (Lower Limb Type)*. [Online]. [Accessed 4 January 2018]. Available from: https://www.cyberdyne.jp/english/products/LowerLimb_nonmedical.html.
22. Walpole, S.C., et al., The weight of nations: an estimation of adult human biomass. BMC Public Health, 2012. 12(1): p. 439.
23. Cyberdyne. *HAL for Medical Use (Lower Limb Type)*. [Online]. [Accessed 4 January 2018]. Available from: https://www.cyberdyne.jp/english/products/LowerLimb_medical.html.
24. Grasmucke, D., et al., Experiences in four years of HAL exoskeleton SCI rehabilitation. Converging Clinical and Engineering Research on Neurorehabilitation Ii, Vols 1 and 2, 2017. 15: p. 1235-1238.
25. Cruciger, O., et al., Impact of locomotion training with a neurologic controlled hybrid assistive limb (HAL) exoskeleton on neuropathic pain and health related quality of life (HRQoL) in chronic SCI: a case study. Disability and Rehabilitation-Assistive Technology, 2016. 11(6): p. 529-534.
26. Fujii, K., et al., The voluntary driven exoskeleton Hybrid Assistive Limb (HAL) for postoperative training of thoracic ossification of the posterior longitudinal ligament: a case report. Journal of Spinal Cord Medicine, 2017. 40(3): p. 361-367.
27. Sanz-Merodio, D., et al. A lower-limb exoskeleton for gait assistance in quadriplegia. in 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO). 2012.
28. Sancho-Perez, J., et al., Mechanical description of ATLAS 2020, a 10-DOF paediatric exoskeleton. Advances in Cooperative Robotics, 2017: p. 814-822.
29. Sanz-Merodio, D., et al., Control architecture of The ATLAS 2020 lower-limb active orthosis. Advances in Cooperative Robotics, 2017: p. 860-868.
30. Marsi Bionics. *ATLAS 2030*. [Online]. 2017. [Accessed 12 July 2017]. Available from: http://www.marsibionics.com/products/?lang=en#/atlas-2030.
31. Rossi, S., et al. WAKE-up: a wearable ankle knee exoskeleton. in 5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics. 2014.
32. Patane, F., et al., WAKE-up exoskeleton to assist children with Cerebral Palsy: design and preliminary evaluation in level walking. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2017. PP(99): p. 1-1.
33. Lerner, Z.F., et al., A robotic exoskeleton for treatment of crouch gait in children with cerebral palsy: design and initial application. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2017. 25(6): p. 650-659.
34. Bayón, C., et al. CPWalker: robotic platform for gait rehabilitation in patients with cerebral palsy. in 2016 IEEE International Conference on Robotics and Automation (ICRA). 2016.
35. Calabro, R.S., et al., Robotic gait rehabilitation and substitution devices in neurological disorders: where are we now? Neurological Sciences, 2016. 37(4): p. 503-514.
36. Lo, H.S. and S.Q. Xie, Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects. Medical Engineering & Physics, 2012. 34(3): p. 261-268.

37. Aliman, N., R. Ramli, and Sallehuddin M. Haris, Design and development of lower limb exoskeletons: A survey. Robotics and Autonomous Systems, 2017. 95: p. 102-116.
38. Esquenazi, A., M. Talaty, and A. Jayaraman, Powered exoskeletons for walking assistance in persons with central nervous system injuries: A narrative review. Pm&R, 2017. 9(1): p. 46-62.
39. Gopura, R., et al., Developments in hardware systems of active upper-limb exoskeleton robots: A review. Robotics and Autonomous Systems, 2016. 75: p. 203-220.
40. Viteckova, S., P. Kutilek, and M. Jirina, Wearable lower limb robotics: A review. Biocybernetics and Biomedical Engineering, 2013. 33(2): p. 96-105.
41. Fahn, S., Classification of movement disorders. Movement Disorders, 2011. 26(6): p. 947-957.
42. Schlaggar, B.L. and J.W. Mink, Movement disorders in children. Pediatrics in Review, 2003. 24(2): p. 39-50.
43. McIntyre, S., et al., Cerebral Palsy—Don't Delay. Developmental Disabilities Research Reviews, 2011. 17(2): p. 114-129.
44. Goodwin, J., et al., Understanding frames: A UK survey of parents and professionals regarding the use of standing frames for children with cerebral palsy. Child Care Health and Development, 2018. 44(2): p. 195-202.
45. Novak, I., et al., Clinical prognostic messages from a systematic review on cerebral palsy. Pediatrics, 2012.
46. Pereira, A., et al., How executive functions are evaluated in children and adolescents with cerebral palsy? A systematic review. Frontiers in Psychology, 2018. 9(21).
47. Alias, L., et al., Improving detection and genetic counseling in carriers of spinal muscular atrophy with two copies of the SMN1 gene. Clin Genet, 2014. 85(5): p. 470-5.
48. Mercuri, E., E. Bertini, and S.T. Iannaccone, Childhood spinal muscular atrophy: controversies and challenges. The Lancet Neurology, 2012. 11(5): p. 443-452.
49. Wang, C.H., et al., Consensus statement for standard of care in spinal muscular atrophy. J Child Neurol, 2007. 22(8): p. 1027-49.
50. Lally, C., et al., Indirect estimation of the prevalence of spinal muscular atrophy Type I, II, and III in the United States. Orphanet Journal of Rare Diseases, 2017. 12(1): p. 175.
51. Christie-Brown, V., J. Mitchell, and K. Talbot, The SMA Trust: the role of a disease-focused research charity in developing treatments for SMA. Gene Ther, 2017. 24(9): p. 544-546.
52. Talbot, K. and E.F. Tizzano, The clinical landscape for SMA in a new therapeutic era. Gene Ther, 2017. 24(9): p. 529-533.
53. Genetics Home Reference. *Spinal Muscular Atrophy*. [Online]. [Accessed 23 February 2018]. Available from: https://ghr.nlm.nih.gov/condition/spinal-muscular-atrophy.
54. Ogino, S., R.B. Wilson, and B. Gold, New insights on the evolution of the SMN1 and SMN2 region: simulation and meta-analysis for allele and haplotype frequency calculations. Eur J Hum Genet, 2004. 12(12): p. 1015-23.
55. Monges, S. and A.L. Rosa, Management of neuromuscular diseases and spinal muscular atrophy in Latin America. Gene Ther, 2017. 24(9): p. 578-580.
56. Hoy, S.M., Nusinersen: First Global Approval. Drugs, 2017. 77(4): p. 473-479.
57. Chiriboga, C.A., et al., Results from a phase 1 study of nusinersen (ISIS-SMN_{Rx}) in children with spinal muscular atrophy. Neurology, 2016. 86(10): p. 890-897.
58. Pechmann, A., et al., Single-center experience with intrathecal administration of Nusinersen in children with spinal muscular atrophy type 1. European Journal of Paediatric Neurology, 2018. 22(1): p. 122-127.
59. Bishop, K.M., J. Montes, and R.S. Finkel, Motor milestone assessment of infants with spinal muscular atrophy using the Hammersmith infant neurological exam-part 2: experience from a Nusinersen clinical study. Muscle & Nerve, 2018. 57(1): p. 142-146.
60. O'Connor, P.J., Trends in spinal cord injury. Accident Analysis & Prevention, 2006. 38(1): p. 71-77.
61. Vogel, L.C., Analysis of ambulation in children and adolescents with spinal cord injuries. Pediatric Gait: a New Millennium in Clinical Care and Motion Analysis Technology, 2000: p. 84-91.
62. Shepherd Center, *Understanding Spinal Cord Injury*. [Online].2011. [Accessed 27 January 2018]. Available from: http://www.spinalinjury101.org/details/levels-of-injury
63. Vitale, M.G., et al., Epidemiology of pediatric spinal cord injury in the United States: years 1997 and 2000. J Pediatr Orthop, 2006. 26(6): p. 745-9.
64. Dhillon, J.K., et al., US Estimates of pediatric spinal cord injury: implications for clinical care and research planning. Journal of Neurotrauma, 2017. 34(12): p. 2019-2026.
65. World Health Organization. *Spinal Cord Injury*. [Online]. 2013. [Accessed 1 March 2018]. Available from: http://www.who.int/mediacentre/factsheets/fs384/en/.
66. Parent, S., et al., Spinal cord injury in the pediatric population: A systematic review of the literature. Journal of Neurotrauma, 2011. 28(8): p. 1515-1524.
67. Jeong, G., B.C. Lim, and J.H. Chae, Pediatric stroke. J Korean Neurosurg Soc, 2015. 57(6): p. 396-400.
68. Child Neurology Foundation. *Stroke in Children - Child Neurology Foundation.* [Online]. [Accessed 3 March 2018]. Available from: http://www.childneurologyfoundation.org/disorders/stroke-in-children/.
69. Tsze, D.S. and J.H. Valente, Pediatric stroke: A review. Emergency Medicine International, 2011. 2011: p. 734506.
70. Powars, D., et al., The natural history of stroke in sickle cell disease. The American Journal of Medicine, 1978. 65(3): p. 461-471.
71. Kissela, B.M., et al., Age at stroke: Temporal trends in stroke incidence in a large, biracial population. Neurology, 2012. 79(17): p. 1781-1787.
72. Anthony, R.R. and E.S. Roach, Topical review article: etiology of stroke in children. Journal of Child Neurology, 1993. 8(3): p. 201-220.
73. Earley, C.J., et al., Stroke in children and sickle-cell disease. Neurology, 1998. 51(1): p. 169.
74. Meyer-Heim, A.D. and E. Boltshauser, Spontaneous intracranial haemorrhage in children: aetiology, presentation and outcome. Brain and Development, 2003. 25(6): p. 416-421.
75. deVeber, G., et al., Stroke in children: recognition, treatment, and future directions. Semin Pediatr Neurol, 2000. 7(4): p. 309-17.
76. Genetics Home Reference. *Spina bifida*. [Online]. [Accessed 3 March 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/.
77. National Health Service. *Spina bifida - NHS.UK*. [Online]. 2018. [Accessed 3 March 2018]. Available from: https://www.nhs.uk/conditions/spina-bifida/.

Appendix A. SPECIFICATIONS OF ALL EXOSKELETONS COVERED IN THE PAPER

Exoskeleton	Total DOF	Weight	Approval	Actuator Type	Actuated Joints	Self-balance control	Stage
ReWalk [3]	6 DOFs	23 kg	FDA	DC motor	Hip and knee	No	Commercial
Indego [9]	6 DOFs	12 kg	FDA	DC motor	Hip and knee	No	Commercial
REX [11]	10 DOFs	48 kg	CE Marking	Electric motor	Hip, knee and ankle	Yes	Commercial
MindWalker [14]	10 DOFs	28 kg (excluding batteries)	Not approved	SEA	Hip and knee	No	Research/Prototype
HAL-Medical [23]	6 DOFs	12 kg (excluding batteries)	CE Marking	DC servo motor	Hip and knee	Yes	Commercial
EksoGT [17]	6 DOFs	20 kg	FDA	Electric motor	Hip and knee	No	Commercial
ATLAS 2020/2030 [28, 30]	10 DOFs	14 kg	Not approved	DC motor	Hip, knee and ankle	Yes	Research/Prototype (under clinical evaluation process)
WAKE-up [32]	4 DOFs	10 kg	Not approved	RSEA	Ankle and knee	No	Research/Prototype
The Exoskeleton by Lerner et al. [33]	2 DOFs	3.2 kg	Not approved	DC motor	Knee	No	Research/Prototype
CPWalker [34]	6 DOFs	Not mentioned	Not approved	DC motor	Hip, knee and ankle	No	Research/Prototype

Appendix B. MAXIMUM ACHIEVED INDEPENDENCY OF INDIVIDUALS FOR EACH LEVEL OF DISORDER

Disorder/Disease	Type/Level	Maximum achieved independency
CP	Level I	Sit and walk without any assistance
	Level II	Sit with minor balance issues, walk with assistive devices
	Level III	Walk only for short distances
	Level IV	Creep only for short distances
	Level V	Cannot sit/walk independently
SMA	Type I	Never sit unassisted or support their head
	Type II	Sit, but never stand or walk independently
	Type III	Can stand and walk in the early periods (but then cannot)
	Type IV	Stand and walk (might lose these abilities)
SCI	High-cervical nerves damage (C1 – C4)	Fully paralyzed, difficulties in breathing
	Low-cervical nerves damage (C5 – C8)	Paralysis in lower extremities, cannot walk
	Thoracic nerves damage (T1 – T12)	Normal use of upper-body, might stand on a standing frame
	Lumbar nerves damage (L1 – L5)	Functional impairments in the hips and legs, might walk with assistive devices
	Sacral nerves damage (S1 – S5)	Temporary loss of some lower-body functions, could walk with assistive devices
Stroke	Ischemic stroke	Highly likely to have permanent weakness of one side of body
	Haemorrhagic stroke	Highly likely to have permanent weakness of one side of body
Spina Bifida	Myelomeningocele	Highly likely paralysis of lower-body
	Meningocele	Highly likely paralysis of lower-body
	Spina bifida occulta	Sit and walk without any assistance