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Toward Standardizing the Classification of Robotic Gait Rehabilitation Systems

Salheddine Ayad, Mohammed Ayad, Abdelkader Megueni, Erika G. Spaich and Lotte N.S. Andreasen Struijk

***Abstract*— With the existence of numerous rehabilitation systems, their classification and comparison becomes difficult, especially when considering many factors. Moreover, most current reviews are descriptive and do not provide systematic methods for the visual comparison of systems. This review proposes a method for classifying systems, representing them graphically to easily visualize all characteristics of different systems at the same time. This method could be an introduction for standardizing the evaluation of gait rehabilitation systems. The method evaluates four main robotic modules, body weight support, reciprocal stepping mechanism, pelvis mechanism and environment module, of 27 different gait systems based on a set of characteristics. The combination of these modular evaluations provides a description of the system "in the space of rehabilitation". The evaluation of each robotic module, based on specific characteristics, showed diverse tendencies. While there is an augmented interest in developing more sophisticated reciprocal stepping mechanisms, few researches are dedicated to enhance the properties of pelvis mechanisms.**

***Index Terms*— gait robotic systems, rehabilitation robotics, standards of classification, visual comparison.**

I. INTRODUCTION

According to the World Health Organization WHO [1], 15% of the global population were estimated to be living with some form of disability in 2010, of which 2.2% have very significant functional difficulties and 3.8% have severe disabilities. This is an increase of 50% over the last 40 years [1]. Neurological disorders are the leading cause of permanent disability worldwide. They can occur as a result of damage to any part of the nervous system, such as the brain, spinal cord or other nerves and tissues, from disease (e.g. stroke, multiple sclerosis) or injury (e.g. spinal cord injuries, brain trauma) [2]. Besides the depressing pain that these individuals suffer, they may also experience physical complications such as muscle atrophy, numbness, and loss of sensation [3], [4]. Hence, various functions necessary for daily living will be affected [5], such as grasping and walking ability which is the focus of this review.

Rehabilitation after neurological disorder is one of the main methods used for recovering and improving the patient's quality of life [6], aiming to help patients with physical impairments to restore their abilities to control their muscles and nervous systems normally [7]. From a therapeutic perspective, the rehabilitation process to regain meaningful mobility in the event of a neurological disorder can support or involve the application of any method or technique aiming to stimulate the nervous system to create new neurological paths to replace the damaged pathways [8]. The process known as "neural plasticity" was the basis for proposing various gait recovery approaches [9], with rehabilitation toward gait recovery heavily reliant on the "physical exercises" approach [10].

Motor learning of neurological disorder rehabilitation relies on three main determinants: practice, specificity, and effort [11]. Practice is related to the duration and intensity of training, more practice will result in more learning [12]. Specificity describes a set of specific oriented tasks, which aim to teach patients some or all functions generally involved in human locomotion, so that the patient should ultimately be able to walk in a more natural way [13]. Effort indicates the degree of patient self-participation in the training, which is required for facilitating motor learning [14].

The clinical-based gait rehabilitation program implies the execution of five major tasks [15] and involves enhancing muscle strength, maintaining balance control, training to gait, providing pelvic control and assisting for various locomotion types of activities of daily living (ADL). It is supposed that the application of those specific tasks with respect to the two other gait rehabilitation principles (practice and effort) will result in significant motor recovery.

Conventional therapies include the treadmill and body weight support (BWS) technology, which has had a great direct impact on facilitating motor learning training and motor recovery [16]–[19]. The interpretation of such positive outcomes relative to the three motor learning determinants can

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be summarized as:

1) Increase the practice rate: the combination of the treadmill with partial body weight support offers a good framework for increasing the number of repetitions and functional gains [20], [21].

2) Ability to perform more than one specific task simultaneously: the patients in the early stage of rehabilitation can perform many specific tasks at the same time due to the body weight support that allows the therapist to assist the pelvis motion and leg swing, while maintaining balance and stability [22].

Nonetheless, robotic rehabilitation has many advantages compared to conventional therapy, allowing more intensive repetitive motions, relieving therapists from the heavy burden, and providing measuring tools to quantitatively assess the level of motor recovery.

Initially, robotic therapy appeared to overcome the limitations of conventional therapy in terms of motor recovery. However, many meta-analysis studies showed no difference between robotic and conventional gait therapy in promoting motor recovery of neurological disorders [23]. Statistics show that only 65% to 70% of stroke survivors learn to walk independently by 6 months post-stroke [24]. Among them, few can be described as having a good quality of gait.

Many systematic reviews have compared the engineering aspects (e.g. mechanical, control etc.) of current robotic systems [25]–[28]. Although most of these studies succeeded in including and describing current systems, they failed to illustrate the position of each system in the global field. Therefore, we questioned whether it was possible to generate a graphic representation of the systems to allow the reader to perceive and compare the main aspects of each system.

The main goal of this review is to classify different rehabilitation systems, graphically and simply representing the main aspects without too much textual description. Such a representation could be introduced to standardize the evaluation of robotic gait rehabilitation systems, thereby helping researchers to identify the system weaknesses, thus make improvements.

The process of classifying robotic gait rehabilitation systems is performed in four steps, which are also the four main sections of this review:

- Step 1 Systems identification: the first step concerns collecting data on current gait systems for the analysis, standardization and evaluation. The next section describes the method we followed to achieve this. A detailed technical description of most current gait systems are shown at the end of the section in a comprehensive table.
- Step 2 Features analysis involves two main steps:
    - Global features analysis which consists of analyzing the three main aspects of the gait robotic intervention (patient, rehabilitation approach and environment) and describing them relevant to a technical characteristic representation. Accordingly, the key elements of rehabilitation interventions required for gait robotic systems to provide can clearly be defined and classified.
    - Robotic features analysis which involves analyzing the current robotic gait systems and suggesting the best robotic module classification to incorporate the set of the defined features (defined in the previews step).
- Step 3 Classification which comprises:
    - Elementary characteristics description, whereby the elementary characteristics measuring the ability of each robotic module to execute the predefined feature are defined.
    - Weighting, due to the difference in importance of different elementary characteristics of robotic modules relevant to the set of required features, each characteristic should be weighted. Therefore, we have proposed two approaches for weighting.
- Step 4 Application: In this step, the different steps described in different rehabilitation robotic systems are applied for a classification.

An overview of the review methodology process in shown in Fig. 1, in which the relation between the pre-mentioned steps is described using a bock diagram.

II. GAIT ROBOTIC REHABILITATION SYSTEMS: DATA COLLECTION

A. Identification

For a quantitative and qualitative database of most existing robotic systems for gait rehabilitation, a total of 35 reviews of

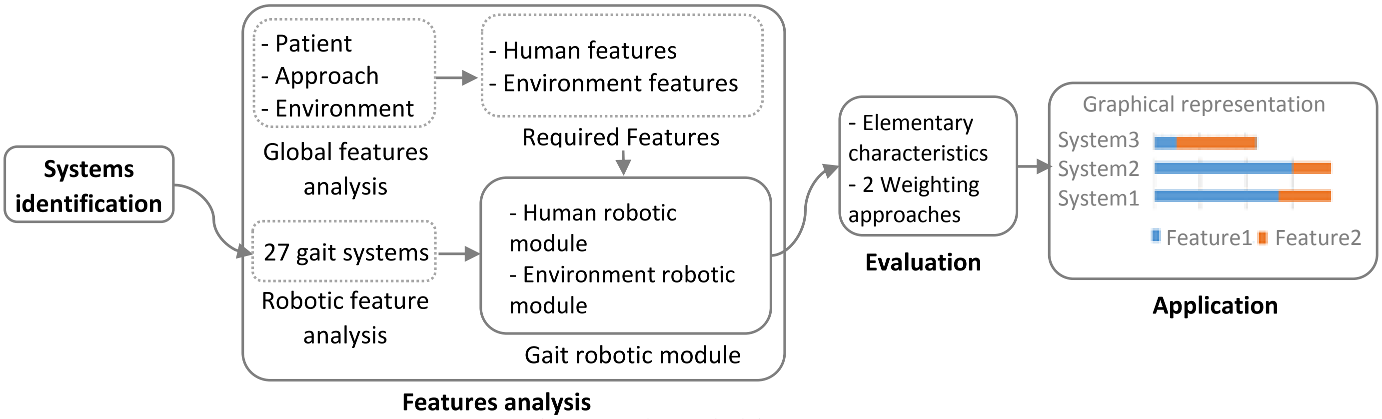

Figure 1. Review methodology process

different lower limb rehabilitation robotics where selected [25], [29]. Then, an automatic algorithm was applied using relevant keywords classified according to four defined issues: "related to robot description", "related to limb location", "related to rehabilitation", and "related to the patient case". For the keyword "Robotic", "Systems", "Robot" refer to "Related to robot description" class…etc. The search function was based on the keyword classification and created the best search request formula relevant to the desired criteria, for example, *"(New OR novel) AND (Robotic OR Robot OR Device OR Manipulator OR End-Effector OR Orthosis OR Treadmill OR biomechanical OR Locomotion OR Platform-Based OR Bio-Robotic OR Prosthetics) AND (Lower limb OR Lower limb OR Lower Extremity OR hip OR ankle OR leg)"*). The databases Scopus, PubMed, Science Direct, Google scholar, IEEE Xplore, MEDLINE, SpringerLink, Compendex, and EMBASE were searched using different search phrases generated by the search function.

B. Inclusion and exclusion criteria

The scope of this review is generally limited to the devices mainly designed for regaining gait function through physical rehabilitation, which target patients with neurological disorders. This review excluded passive systems mainly used for stretching muscles, such as those used for specific types of exercises, like isometric etc., since they cannot supply the affected limbs with the required energy to complete the rehabilitation task. Also, assistive systems not clinically supervised or not developed for a therapeutic goal were excluded.

C. Selection result

In total, 27 gait robotic systems were selected for this study. These systems can be classified into three mechanical groups, treadmill-based devise, footplate-based devices and over ground based devices, as shown in Table 1.

D. Table notes

All system characteristics are presented relevant to the technical characteristic representation described in the next section to compare the extent of such system in supporting features of the basic gait robotic modules, that is, human robotic modules and environment robotic module (separated with a thick bold row lines).

The identity information section contains basic and general information describing the systems, including the name of the system (marked in bold), year of development, country of origin, stage of development, i.e., is it a prototype or commercial system (followed by their producer names), total of active actuated Degree Of Freedom (DOF) and type of the system (treadmill, footplates or over ground based system).

The human robotic modules section contains information about the three robotic modules, body weight support, reciprocal stepping mechanism and pelvis mechanism, used for assisting the patient gait movement (separated with a dark black line), in addition to information about body weight shifting. The BWS (row) indicates the type of the mechanical designed supported, cable body weight support (cBWS) and structure body weight support (sBWS). Body weight shifting (row) indicates if the system supports the feature of BWS or not (Yes/No). The reciprocal stepping and pelvis mechanism robotic parts contain information regarding the degrees of freedom of the robotic module (DOF) and Mechanical design. There are four states of DOF, A: active, P: passive (i.e. exerting only resistive force), F: free (neither active nor passive force is exerted), and R: restricted certain criteria. For movements designation: FE: flexion/extension, AA: abduction/adduction, IE: indorotation/exorotation. LR: left/right, FB: forward/backward, UD: up/down, PR: pelvis rotation, PT: pelvic tilt, PM: pelvic rotation about the mediolateral axis.

Two features were considered for the mechanical design, type of actuation (if no actuator is introduced to support movement in a certain direction, the "No" mark is filled, other designation are AC: alternating current, DC: direct current) and power of transmission (note: for lack of data, this features has not described the pelvis mechanism).

The environment robotic module contains physical properties and visual properties, Yes/No marks are used for checking if the system simulates different types of grounds and if it can complete the physical properties of simulated terrain with visual feedback (VR: virtual reality, AR: actual reality).

III. FEATURES ANALYSIS

A. Gait based elements (patient, robot, environment)

For the integration of robots in rehabilitation, engineers depended largely on their designs to imitate therapist movements [25], [28], [30]. The movements that the robots tried to perform were originally set by rehabilitation programs to satisfy the requirements of the period of the pre-robotic age. Consequently, many weaknesses not addressed by conventional therapy were also inherited by robotic therapy. Robotic therapies could benefit from different rehabilitation philosophies that are independent of the conventional therapy way of thinking.

Firstly, the relationship between the walker and the environment should be well understood with respect to the set of characteristics defined by a descriptor. The different rehabilitation and engineering aspects could then be described from the perspective of maintaining this natural relationship.

The actual walking process in the case of a healthy person can be described as a direct relationship between the walker and the environment in which the walker performs a set of movements, while the ground responds with a set of physical reactions allowing the walker to change their location. However, due to the disability, this reciprocal relationship can be missing or weakened from the patient side, which could be repaired either with assistive tools (such as crutches or assistive robotic devices) [31]–[33] or simply by restoring the damaged function through therapeutic rehabilitation. The latter consists of two main elements, approach and executive. The approach is the "software", while the executive is the "hardware" (Fig. 2).

In addition, the environment where the executive executes the approach could have more importance. For instance, the type of ground on which the executive tries to teach the patient to walk may affect the quality of the result. An ideal program should account for different ground shapes (plane, stairs…etc.), considering the patient's situation as well as the environment. An ideal system should be able to simulate the environment

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TABLE 1. ROBOTIC DEVICES FOR GAIT REHABILIATION

Identity information	System					**LOPES II** [34]	**LOPES** [35]–[38]	**PAM & POGO** [39]–[41]
	Year					2014	2007	2003
	Country					Netherland	Netherland	USA
	Development stage					Commercial (Moog)	Prototype	Prototype
	Total DOF					8	8	9
	Type					Treadmill	Treadmill	Treadmill
Human Robotic modules	**Body weight support**					BWSc	BWSc	BWSc
	Reciprocal stepping mechanism	DOF			Hip (FE-AA-IE)	A-A-F	A -A -R	A-P-R
					Knee (FE)	A	A	A
					Ankle (FE-AA-IE)	P-P-P	F-F-F	F-F-F
		Mechanical design	Actuation		Hip	Servo motor 40N.m, gear ratio (2/3)	Servo motor (max speed: 8000rmp; power: 567 W; continuous torque 0.87Nm; peak torque 2.73 Nm) gear ratio (64/1)	Pneumatic cylinders (Length =25cm)
					Knee	Servo motor 100N.m, gear ratio (3/2)		
					Ankle	No	No	No
			Power transmission			Push-pull rods	Bowden cable drive + springs (at hip and knee flexion) (Stiffness 35.1 KN/m) (hip abduction)	Pneumatic cylinders
	Pelvis mechanism	DOF	Translation		LR	A	A	A
					FB	A	A	A
					UD	P	P	A
			Rotation		PR	P	R	A
					PT	P	R	A
					PM	R	R	P
		Mechanical design	Actuation	Translation	LR	Servomotor (torque 40Nm) (gear ratio 0.2)	DC motor (max speed: 6000rmp; power: 690 W; peak torque 2.2 Nm) gear ratio (8/1) + springs (stiffness 3.98 KN/m)	Pneumatic cylinders (Length =25cm)
					FB	Servomotor (torque 100 N.m)	Linear actuator (power: 250 W; peak force 204 N)	
					UD	No	No	
				Rotation	PR	No	No	
					PT	No	No	
					PM	No	No	No
	Body weight shifting					No	No	No
Environment robotic module	Physical properties	Simple ground				Yes	Yes	Yes
		Complex ground				No	No	No
		Challenges				No	No	No
	Visual property	VR				No	No	No
		AR				No	No	No

TABLE 1. ROBOTIC DEVICES FOR GAIT REHABILIATION *(CONTINUED)*

LOKOMAT [42]–[45]	**ALEX** [46]–[49]	**ALEX II** [50]	**UoA PMAbot** [51], [52]	**ARTHuR** [53]–[55]	**STRING-MAN** [56]	**RGR** [21], [57], [58]	**MIT-Skywalker** [59]–[61]
2000	2007	2011	2012	2002	2003	2010	2010
Switzerland	USA	USA	New Zealand	USA	Germany	USA	USA
Commercial (Hocoma)	Prototype	Prototype	Prototype	Prototype	Prototype	Prototype	Prototype
4	4	4	4	2	6	1	4
Treadmill	Treadmill	Treadmill	Treadmill	Treadmill	Treadmill	Treadmill	Treadmill
BWSc	BWSs	BWSs	BWSc	BWSc	Developed BWSc	No	BWSc passive
A(50)-P-R	A-P-R	A-P-R	A-P-R	A_F_F	F-F-F	P-P-P	F-F-F
A(50)	A	A	A	A	F	P	F
P-P-P	F-F-F	F-F-F	A-P-P	F_F_F	F	F-F-F	A-A-P
DC motor	Linear actuator	Rotary motor + gear ratio (1/50 integrated with motor) + (1/60)	PMA	Coil linear motor	No	No	No
	Linear actuator (peak torque 100 N.m)		No	No	No	No	No
No	No	No	No	No	No	No	Brushless servomotor
Precision Ball Screw	Linear actuator	Gear drive	PMA (length: 34cm) (braid diameter: 3cm) (Peak torque at the joint 50 N.m)	Rigid links	Wires	No	Treadmill belt
P	R	P	R	F	A	P	R
R	R	P	R	F	A	P	R
P	P	P	P	F	A	F	F
R	R	P	R	F	A	F	R
R	R	P	R	F	A	A	F
R	R	R	R	F	A	F	R
No	No	No	No	No	Electrical motor	No	No
No	No	No	No	No		No	No
No	No	No	No	No		No	No
No	No	No	No	No		No	No
No	No	No	No	No		Linear actuator	No
No	No	No	No	No		No	No
No	No	No	No	No	_	_	No
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No	No	No	No	No	No	No	No
No	No	No	No	No	Yes	No	Yes
Yes	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No

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TABLE 1. ROBOTIC DEVICES FOR GAIT REHABILIATION *(CONTINUED)*

HapticWaker [62]–[65]	**G-EO- system** [66]–[68]	**ULRF** [69]–[72]	**LOKOIRAN** [73], [74]	**ICARE** [75]–[77]	**GM5** [78]	**Gait Master 2** [79]	**GT (Gait Trainer)** [80]–[83]
2004	2010	2007	2013	2010	2010	2002	1999
Germany	Germany	Korea	Iran	USA	Japan	Japan	Germany
Prototype	Commercial (Rehatechnology)	Prototype	Prototype	Commercial (sportsartamerica)	Prototype	Prototype	Commercial (Reha-Stim)
6	6	6	4	4	4	4	4
Footplates	Footplates	Footplates	Footplates	Footplates	Footplates	Footplates	Footplates
BWSc	BWSc	BWSc	BWSc	BWSc	Safety frame	BWSc	BWSc
A-R-R	A-R-R	A	A-R-R	A-R-R	A-R-R	A-R-R	A-R-R
A	A	A	A	A	A	A	A
A-R-R	A-R-R	A-R-R	R-R-R	P-R-R	P-P-R	R-R-R	R
Linear motor + Electrical motor	1500W Servo motor 400 W Servo motor	Linear actuators + AC servo motor	AC motor	Electric motor	Linear actuator + AC servomotor	AC servomotor	Electric motor
No	No	No	No	No	No	No	No
No	No	No	No	Crank-rocker	Parallel arms	Crank-rocker	Double crank + rocker gear
Rails + parallel arm	Rail + parallel arm	Parallel Mechanism + Sliders	Parallel arm	F	F	F	F
F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F
F	F	F	F	F	F	F	F
F	F	F	No	No	No	No	No
No	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No
No	No	No	No	No	No	No	No
Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Yes	Yes	Yes	No	No	No	Yes	No
No	No	No	No	No	Yes	Yes	No
Yes	Yes	Yes	No	No	No	No	No
No	No	No	No	No	No	No	No

TABLE 1. ROBOTIC DEVICES FOR GAIT REHABILIATION *(CONTINUED)*

DSP [84]	**WalkTrainer** [85], [86]	**NaTUre-gaits** [15], [87]–[89]	**BAR** [90]	**KineAssist** [91], [92]	**WHERE-II** [93]	**WHERE-I** [93]	**GaitEnable** [94]
2005	1st version (2006) 2nd version (2009)	2011	2016	2005	2009	2009	2012
USA	Switzerland	Singapore	Slovenia	USA	Korea	Korea	Canada
Prototype	Commercial (Swortec SA)	Prototype	Prototype	Commercial (Kinea Design LLC)	Prototype	Prototype	Prototype
12	12	11	3	_	_	_	_
Footplates	Over ground	Over ground	Over ground	Over ground	Over ground	Over ground	Over ground
BWSc	BWSc	BWSs	BWSs	BWSs	BWSc	BWSs	Passive BWS
A-A-P	A-R-R	A-R-R	No	No	No	No	No
A	A	A	No	No	No	No	No
A-A(40)-A(25)	A-R-R	A-R-R	No	No	No	No	No
Pneumatic pistons	DC motors	DC brushless motors	No	No	No	No	No
			No	No	No	No	No
Pneumatic pistons	Precision ball screw	Gears	No	No	No	No	No
F	A	A	A	P	F	R	R
F	A	A	A	P	F	P	F
F	A	A	P	P	F	P	F
F	A	A	A	P	F	R	F
F	A	A	P	P	F	R	F
F	A	P	P	P	F	R	F
No	DC motors	DC brushless motors	Linear actuators	No	No	No	No
No				No	No	No	No
No			No	No	No	No	No
No			Linear actuators	No	No	DC motor, gear ratio (150:1)	No
No			No	No	No	No	No
No		No	No	No	No	No	No
No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No	Yes	Yes	Yes	_	Yes	Yes	_
No	No	Yes	Yes	_	Yes	Yes	Yes
No	No	No	No	No	No	No	No
Yes	No	No	Yes	Yes	No	No	No
Yes	No	No	No	No	No	No	No
No	Yes	Yes	Yes	yes	yes	yes	yes

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with all its complexity. Then, the relationship between the patient and the environment should be managed throughout the approach. Fig. 2 describes graphically the relation between the different gait elements in the case of a healthy person and a paralyzed subject.

The different elements of the chain Patient-Rehabilitation-Environment will be discussed in the following sections.

1) Approach

Most physical rehabilitation approaches adopt the three principles of specificity, practice, and effort.

a) Specificity

The specificity can be described by a set of movements that should be supported in order to imitate natural gait movements. In conventional therapy, this sets to five specified oriented tasks, whereas the terms features and activities are used in robotic rehabilitation [15]. The features are simply the characteristics the gait robotic system should provide to help implement the activities. Five different features are selected based on the theoretical basis of locomotor training: body weight support, balance and truck stability, reciprocal stepping, pelvic motion and body weight shifting [95].

For the governing conditions of their implementation, these can be elected in association with the biomechanics of movements of the supported activity. The activities are just a set of associated locomotion movements prescribing the type of gait patterns allowing the walker to navigate through the different types of ground.

b) Practice

The practice determinant can be easily measured using two benchmarks emphasized by both rehabilitation interventions, duration, which refers to the time involved in one training session, and intensity, which is the number of training sessions within a time period e.g. week, month or year.

c) Effort

This part of the approach refers to the degree of patient self-participation within the training. Generally, at the beginning of the rehabilitation, the patient is not able to participate in the exercise, instead, he is moved by the robot. However, over time, the robot should persuade the patient to participate in the action, thus becoming progressively active and independent. In other words, the robot must have the ability to control and adjust the degree of assistance given to the patient, based on their progress [34].

2) Environment

While both interventions (robotic and manual therapies) support the movement of the patient, they do not provide the patient with the perception of walking on natural ground [58], [89]. The key environment characteristic elements that the rehabilitation interventions should provide must be clearly defined. They include *physical properties*, which are important for the patient to experience during the training process. Walking on simple ground, for example, must provide a reaction force when touching the ground. Also, sight *(visual property*) is important as patients can neglect most signals provided by other senses if they contradict the sight. Therefore, used properly, this property could be very beneficial by enhancing the stimulation of the nervous system for completing the physical properties or for motivating the patient.

With respect to these elements, the robotic systems summarized by this review are compared by their efficiency to simulate for the user, three levels of ground shaping forms selected based on the environment types involved in the clinical program of gait rehabilitation [10]: *simple ground* which refers to the referential ground supported by the task of gait locomotion, such as walking on a flat plane [43]; *complex ground* which could be any form of the ground experienced in daily living environments. However, to be more precise and respecting what exists in clinical programs, this should refer to the ability of teaching the patient to go up/down stairs [96]. Thirdly, *challenges*, which does not refer to a specific type of ground but is important to improve locomotor functions by challenging the patient's level of comfort, for example, subjecting the patient to an actual fall experiment [87] or unstable ground by teaching the patient balance exercises.

3) Patients

The effectiveness of robotic gait rehabilitation largely

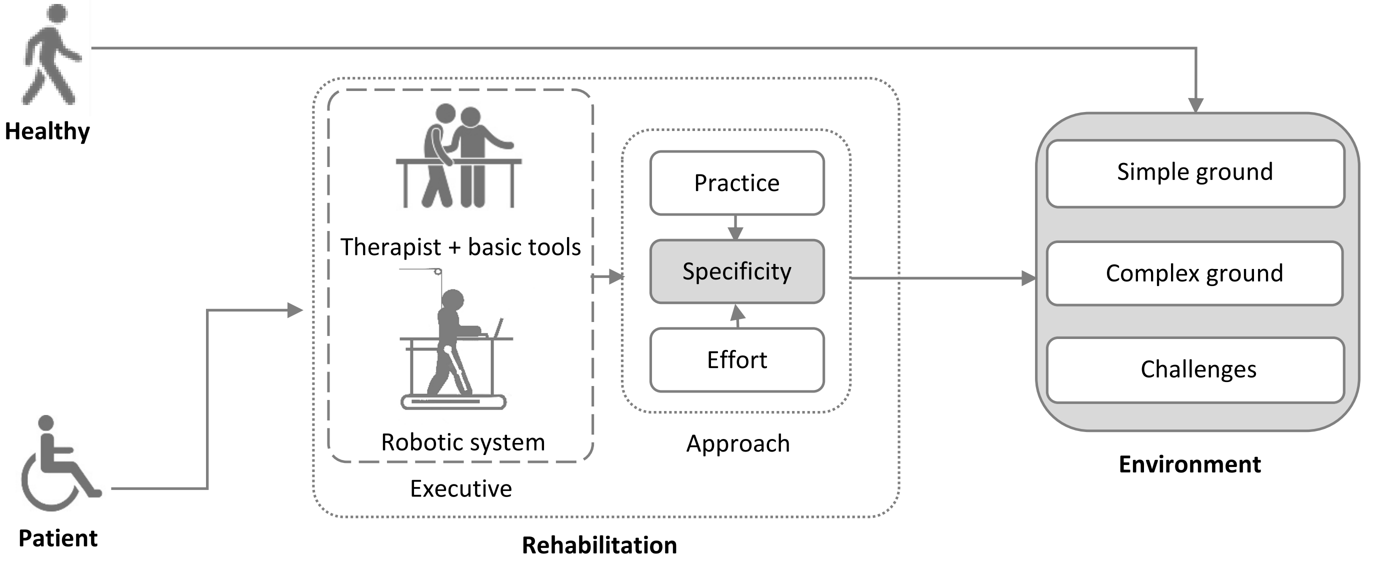

Figure 2. Basic relation patient, environment and robot

depends on the ability of the system to provide different type of assistance according to patients' different recovery stages [97]. The rehabilitation process can broadly be divided into three stages: the preliminary, intermediate and advanced stages [28]. Patients can be classified into eight main groups [98]:

0 = normal
1 = mild disability (no visible gait abnormality)
2 = moderate disability (abnormal gait but no aids)
3 = early cane (patient can walk about 8 m without cane)
4 = late cane (dependent on unilateral support)
5 = bilateral support (scooter for distance)
6 = confined to wheelchair (patient cannot walk about 8 m)
U = unclassifiable (significant cognitive, visual, fatigue, bowel/bladder impairment).

B. Gait robotic modules

In order to respond to the pre-mentioned approach and environment features requirements, the gait robotic rehabilitation systems support two different robotic modules: human robotic modules (since their role consists of assisting or completing the patient movements) and environment robotic modules (since they simulate different ground reaction forces). Fig. 3 describes in detail the relation between the required features (previously described in section "A.1)a)") and the associated robotic modules developed to help to incorporate these features.

1) Human robotic modules

Gait rehabilitation systems can use a combination of three different robotic modules for assisting patient gait movements, of which there is more than one mechanical design, thereby providing a diversity of solutions. These robotic modules are Body Weight Support (BWS), reciprocal stepping mechanism, pelvis mechanism, and body weight shifting cited in the order of their use in gait rehabilitation robots.

a) Body Weight Support

BWS is a mechanical system used to help the patient carry some or the full weight of their body during standing [99], [100]. it provides stability to the trunk and the pelvis during movement, so that the patient performs gait training safely. BWS can be sorted according to the mechanical design into two types:

cBWS supports the patient's weight through an overhead attachment cable, distributing unweighting assistance equally on both sides of the body through the harness fastened around the hip and the abdomen of the patient. In an active dynamic BWS, the attachment of the cable is adjustable to maintain the amount of the prescribed force assistance. Examples of a gait rehabilitation robot that uses the cBWs system include Lokomat [43], LOPES [36], and G-EO system [62].

sBWS is less commonly used compared to cBWS. For supporting the subject's weight, these systems use a

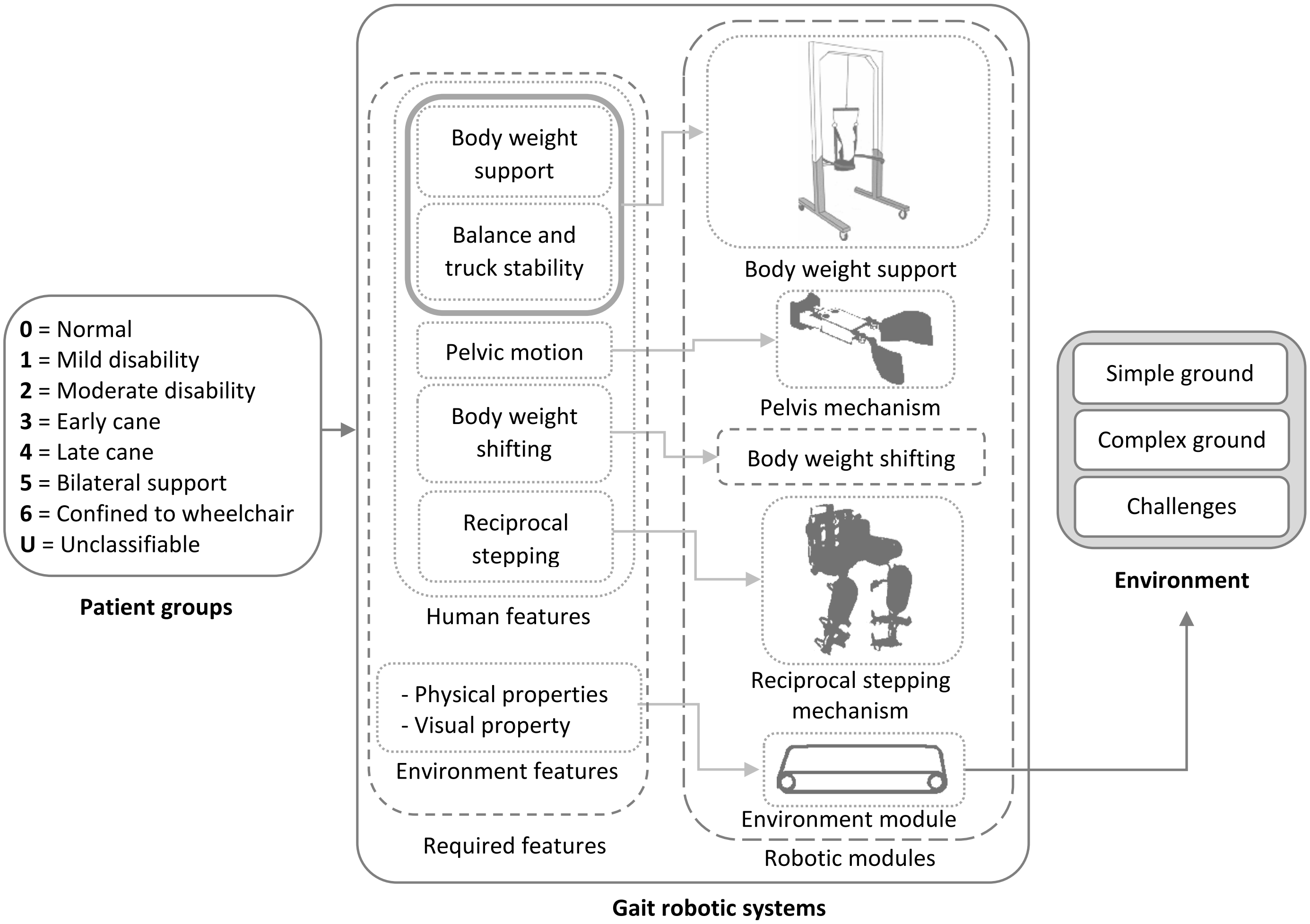

Figure 3. Basic robotic modules relations

robotic arm holding the patient's waist or back. Examples of gait rehabilitation robots that use cBWS system are KineAssist [87], NaTUre-gaits [15], PAM and POGO[41].

b) *Reciprocal Stepping mechanism*

The reciprocal stepping robotic modules are mechanisms for assisting the movements of the body lower extremities involved in the walking process or other gait patterns. The joints motorized by reciprocal stepping mechanism comprise all the leg joints including the hip, knee, and ankle [101]. It is important to note that the largest proportion of the robotic research on gait rehabilitation systems have focused on developing and enhancing the characteristics of this specific module. In addition, its design is considered very complex due to the number of mobile parts, the Degree of Freedom (DOF), Range of Motion (ROM), and the forces for each of the parts.

The reciprocal stepping mechanisms for assisting in gait locomotion are exoskeleton and end-effector.

Exoskeleton: the exoskeletons are wearable mechanical parts that move in parallel to the skeleton of the patient in a way that no additional active DOF will be required to follow patient movements [36]. In such devices, the exoskeleton is attached to the BWS frame of the gait system at the pelvis level, where the advantage of weight-compensation to the exoskeleton.

End-effector: in this system, the leg movements are controlled by moving the distal parts instead of moving the thigh and shank of the subject. This can be at the foot level using programmable footplates. Based on the trajectory generated, two mechanisms can be distinguished:

- Fixed trajectory: This class groups all the systems where the trajectory is adjusted before starting the exercise. Generally, the trajectory is elliptic and adjusted by changing the size of each member of the crank-rocker mechanism e.g. GT [76] and ICARE [71].
- Dynamic trajectory: This class groups all the systems where the trajectory is not predefined. Typically, it can take any shape within limited ranges according to certain directions e.g. HapticHaker [58] and G-EO system [62].

c) *Pelvis mechanism*

Pelvis is the center of the body weight and the link point between the lower limbs and the trunk, thus it is very important for maintaining balance and transferring forces during walking. Therefore, it is not surprising that three of the six gait determinants are related to pelvis motion [102], and the lack of control of this part will likely disturb the quality of gait rehabilitation. The problems can manifest as secondary gait deviations [21], which may result from abnormal pelvic obliquity.

The pelvis mechanism is a robotic system usually placed at the back of the patient attached to the gait system frame, developed to assist the six pelvis DOF. The comparison between different systems is based on the number of DOF they support. Despite its high importance and impact on quality of gait recovery, few studies have attempted to develop it [21]. Earlier gait robotic systems, such as Lokomat, focused on controlling leg movement, while the pelvis was restricted. Later, it was given more importance and can also be found as a separate system for correcting the deviation from normal pelvic motion.

d) *Body Weight Shifting*

One of the important concepts in the rehabilitation process for a well-trained neurological system is body weight shifting, without which a patient may lose the ability to maintain balance during walking [21]. Body weight shifting can be provided by assisting the pelvis forward translation. Actually, it is difficult for a fixed system to provide such a sensation using limited local motions, for example, a pelvis mechanism with motorized forward and backward motion. However, movable systems can partially provide that.

2) *Environment robotic Modules*

Three known types of mechanisms are used for simulating the environment [28], [25]: treadmill, footplates and over ground. The first two are static systems where the simulation of ground reaction is performed by moving the ground under the patient's feet, while the latter is a movable system, in which the user interacts directly with the ground without simulation. In such a system, the patient travels on real ground, while the system plays the role of assistance or guidance.

- Treadmill is a popular progress method used for locomotor devices, consisting of generating an opposite movement to which the subject is walking or running toward, so he or she stays in the same place. The walker's foot is not in permanent contact with the device, it can be only during the stance phase. With this type of progression method, only a typical flat ground can be simulated.
- Footplates in addition to their role in assisting the patient stepping reciprocal movements as previously mentioned, can be setup to act as an environment simulator [65]. By changing the type of executed control, the footplates can switch from the mode of foot guide assistance to ground simulation. This can be realized by exerting a low impedance force to the patient's feet when they are supposed to be in the air (swing phase), while a high impedance is executed when the feet are in contact with the virtual ground (stand phase) [96]. In a similar way, this mechanism can simulate complex grounds rather than a typical flat ground such as stairs, slope...etc.
- Over ground systems consist of a mobile platform allowing the patient to navigate into the clinical environment. The mobile platform generates the movements through motorized wheels and can be a guide following a straight or curved path [92].

IV. EVALUATION OF GAIT ROBOTIC SYSTEMS

As mentioned earlier, the aim of this review is to make it easy to perceive different gait robotic systems, by classifying them according to certain properties. This classification emphasizes the differences between systems, evaluating the gait systems through the robotic modules comprising the system with coefficients defining the weight of every module. The evaluation of each module is achieved by assessing elementary characteristics (features measuring the ability of each robotic module to execute the predefined feature) with coefficients determining the weight of every element. It is important that weight coefficients can change according to the activity and the patient recovery stage, since the conditions governing these features have changed. The first part of this section discusses the methodology employed for weighting and scoring the features of the different robotic modules. The second part describes the elementary characteristics defined to technically describe the different gait robotic modules.

A. Scoring and weighting

One of the biggest challenges in this study is the evaluation of the systems for a specific feature and the weight of each feature for calculating the global evaluation. The team discussed and analyzed the problem, finally defining two main issues: evaluating the score of the system for a specific feature; and the evaluation of the weight of the feature for a robotic module.

1) Scoring

Three levels of authenticity where determined when scoring a system:

- High, when the information was provided directly from the developer, e.g., a precise value of DOF and ROM (this can be found in catalogs, articles etc.).
- Medium, when the information can be extracted from the description provided by the developer or from other studies.
- Low, when a subjective evaluation of the system was made based on the mechanical design basic elements (type of actuation, power transmission and mechanical configuration).

2) Weighting approaches

Two approaches were adopted for weighting, different features or different robotic modules, where both were based on descriptive evaluations provided by many studies of robotic gait rehabilitation. For instance, if studies confirmed that for a specific stage S1, feature F1 (e.g. balance support) is more important than feature F2 (e.g. pelvic motion assistance), the weight W1 for feature F1 is higher than weight W2 for feature 2. It was observed that the descriptive evaluation could be implicit, for example studies focus more on F1.

The next step was numeric evaluation, and the two approaches were:

- Approach 1: An approximate intuitive value was based on the rank of the features using the descriptive evaluation. The descriptive evaluation is a numeric evaluation with a very low resolution, therefore providing a numeric evaluation is nothing more than increasing the resolution with an amount sufficient to make the scale of evaluation capable of distinguishing differences between systems. Nonetheless, this does not mean that this evaluation is as authentic as measurements.
- Approach 2: After sorting features according to descriptive evaluations, the first feature is awarded the highest value of the scale. The value for the second one is the value of the first multiplied by a factor lower than 1 (for example 0.75), and so on. The goal of this is to make the differences uniform, since actual data is unavailable.

The following expressions are examples of some of the descriptive evaluations used to provide an approximate intuitive value to some features:

“the *main* requirements of the gait rehabilitation robot concern *weight beaning* and *balancing*, as well as *posture control* [56]”,

“a robot, in the *first place*, should allow for a “patient-in-charge” mode where healthy subjects are able to walk unconstrained by the device. This concerns the choice of *DOF* and the quality of low impedance control” [36],

“the reason to *omit* an actuated robotic *ankle joint* was that it is not *necessary* to provide an external *“ankle push-off”* in the device in order to walk safely” [36].

B. Elementary characteristics

Two different groups of characteristics associated with the two types of robotic modules were defined, human and environment modules:

1) Human robotic module characteristics

Dynamic and adjustability: While walking or practicing any exercise, the body moves locally in all directions. A BWS is supposed to carry the body within the exercise, providing constant support of the patient’s body weight [103] during all walking phases. The amount of support provided may be adjusted according to different subject weights and recovery stages. Therefore, the “Dynamic and adjustability” factor assesses the extent to which the system verifies the terms “constant support” and “adjustable support”.

Back-drivability: During rehabilitation exercises, it is possible that the patient suddenly loses control or the ability to move a limb, as well as any unexpected event. Therefore, if the system is not ready to cope quickly with the new situation, it may cause damage to the patient [104]. Moreover, the back-drivability allows the therapist to easily apply certain maneuvers, that is, back-drivability is the ability of the system to show low intrinsic endpoint impedance toward certain force sources [41], thus the patient does face an inertia that could delay the response of the system. Back-drivability can be realized using different methods.

Free movement: This feature verifies whether any part of the system disturbs or prevents the motion of other parts. It is important to notice that the movement of the upper limbs and the trunk are the main concern. Commonly, restriction of the trunk movement occurs by the harness of the cBWS type, and the exoskeleton restricting the arm swinging [34].

DOF: This is one of the basic characteristics for describing the gait system capabilities [34] and refers to the number of independent displacements and rotations. In order to satisfy the movement requirements, the robotic system must be able to support a sufficient DOF, which may change according to the activity. Some activities rely more on certain degrees, while others do not [96]. Any lack in the DOF affects more or less the agility and the comfort according to its importance for the activity [41], [53]. Therefore, this can be defined with regard to pelvis and reciprocal stepping robotic modules as:

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- Pelvis mechanism allows six pelvis movements, three translations: mediolateral (left/right), anteroposterior (forward/backward) and superior-inferior (up/ down), and tree rotations: pelvis rotation, pelvic tilt and pelvic rotation about the mediolateral axis.
- Reciprocal stepping mechanism considers the three main joints of the lower body, hip, knee, and ankle. The hip is a 3 DOF joint, consisting of flexion/extension, abduction/adduction, and internal/external rotation. Although the knee consists of 2 DOF [96],[105], only the flexion and extraction are considered. For most activities, the second one (internal/external flexion) is less important [101], [106]. The ankle joint has 3 DOFs dorsiflexion/plantar flexion, abduction/adduction and internal/external rotation [107].

There are three main states possible for a DOF, free, restricted or assisted. The evaluation in this case, involves restriction and assistance, which can be represented in a two-dimensional space like polar coordinates. The restriction axis corresponds to the impedance the limb is experiences, while the assistance axis corresponds to the acting force. For an assisted system, the motion is provided by the system, while it is a resistive force if it is restricted. As the "free" point is approached, the difference between "restricted" and "assisted" becomes unclear, explaining why this representation was selected. The evaluation is a combination of the two coordinates "restriction" and "assistance", with coefficients defining the weight of each of them, which vary according to the recovery stage. Fig. 4 describes the relation between the 3 states of DOF. The different robotic assistance modes are derived from this relation [97].

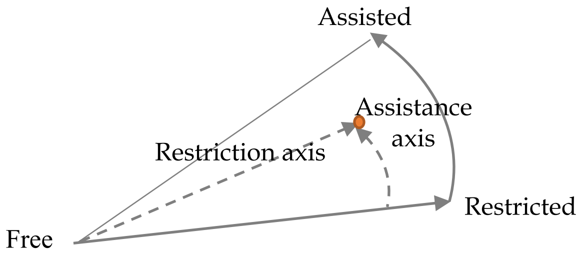

Figure 4. Basic Relation between the 3 states of DOF

ROM: ROM is a concept strongly correlated to the DOF: knowing that the DOF means the possibility to move or rotate in a certain direction, the ROM determines the extent the motion could reach. A limited ROM may cause many disadvantages according to the DOF [108]. For example, in addition to critical balance, restricted motion in the sagittal plan limits the step length and the speed, which may affect the quality of gait training. Therefore, a well-designed system for the ROM [50] should take into account different patient anthropometrics [36], especially the thigh and shank lengths, since they have a direct impact on the step size.

2) *Environment robotic module characteristics*

The evaluation of the environment robotic module can be achieved through an assessment of three characteristics, diversity of grounds, synchronization, and visualization. The first characteristic aims to the check the ability of robotic devices to simulate different type of grounds as discussed. previously. The visualization defines the extent of systems in providing real or virtual feedbacks to patient movement while walking. Since most gait robotic systems use ground simulators, then the system should ensure the walker receives a reaction force the moment he steps on a virtual ground [96]. Therefore, the synchronization term is introduced to evaluate the capacity of different environment modules to realize this requirement.

V. APPLICATION

In order to achieve the goal of classifying and graphically representing the different robotic gait systems, the final step applied the different evaluation steps mentioned in the previous section on the 27 gait systems included in this review. The features of each robotic module were sorted relevant to the methodology described in section IV. Furthermore, the coefficients describing the weights of the features, as well as the weights of the robotic modules were define relevant to *approach 2* described in section IV.A.2.

The first part of this section presents an overview of the sorting of the different feature characteristics. The second part analyses the results of the graphical representation of the modular and global evaluation, providing the review classification.

A. *Features ranking*

The evaluation of every module is the combination of the relevant elementary characteristics with their coefficients. To define the weight coefficients, the features of the different robotic modules including BWS, reciprocal stepping mechanism, pelvis mechanism and body weight shifting, were sorted as follows:

1) *BWS*

Three elementary characteristics important for describing the BWS robotic module were defined: dynamic, back-drivability, and free movement. The importance of these three features could vary according to the level of recovery stage. It was determined that most designs give more importance to "dynamic and adjustability" and free movement, with less to back-drivability. Moreover, free movement becomes more important in the latest stages of rehabilitation since the subject has recovered the ability to move without the need for assistance [109]. Therefore, the features were sorted as follows:

- Early stage: (dynamic, free movement, back-drivability)
- Latest stage: (free movement, dynamic, back-drivability)

2) *Reciprocal stepping mechanism and pelvis mechanism*

The evaluation of the reciprocal stepping and pelvis mechanisms robotic modules was performed through the evaluation of 4: DOF, ROM, back-drivability and free movement . Usually, designers develop their systems to have more DOF and wide ROM [34], [42], [46], than developing a lightweight and high dynamic driving mechanism [39], while the free movement has the lowest priority. Therefore, these

features were sorted as follows:
- (DOF and ROM, back-drivability, free movement).

3) *Body weight shifting*

For body weight shifting, we only determined if the system supported this feature or not, assigning a Boolean value accordingly.

4) *Environment robotic module:*

Three elementary characteristics for evaluating the environment robotic module were defined, two of which related to the physical properties of the simulated environment (diversity of grounds and synchronization) and one to visual feedback. Typically, designers give more importance to physical properties as they directly impact the physical condition of the patient. For the differentiation between the two physical properties, designers give a high priority to enable their system to simulate one or more types of ground [62], [65], while for the synchronization, only a few designers highlighted the importance of such features. Therefore, the environmental features were sorted as follows:
- (diversity of grounds, synchronization, visualization)

Degree of authenticity: There were three levels of authenticity when scoring, the degree of authenticity for each feature in shown in Table 2.

TABLE 2. AUTHENTICITIES OF DIFFERENT ELEMENTORY CHARACTERISTICS

Authenticities	High	Medium	Low
Features	- DOM - ROM - Visualization	- DV - FM - DG	- Back-drivability - Synchronization

DV: Dynamic and Adjustability, FM, Free Movement, DG: Diversity of Grounds

5) *Global evaluation*

The global evaluation is a combination of the modular evaluation with coefficients describing the weight of each robotic module. The robotic modules were included on the basis that they were basic, support more features or support more complex and dynamic movements, so they were sorted as follows:
- (reciprocal stepping, environment module, BWS, pelvis orthosis, body weight shifting).

B. Results

The evaluation was performed using a scale from 0 to 5 and the results shown in Fig. 5, while their global evaluation is shown in Fig. 6. It is important to notice that result of evaluating the BWS is relevant to earlier stage (the more important one[28], [97]) conditions.

C. Results analysis

1) MODULES ANALYSIS

The evaluation of each robotic module based on specific characteristics showed diverse tendencies. For the reciprocal stepping, setting a threshold of 3.5, approximately 63% of the systems could be described as having a good result. In contrast, the pelvis mechanism had a poor average score compared to the other modules, even with a threshold of 2.5, only 22% of the systems satisfied this requirement. For the environmental modules, all the systems satisfied the basic requirements of environment ground for assisting sample locomotor training, of which only 19% were able to support more advanced ADL training. All systems were dynamic trajectory footplates based devices.

Dynamic and adjustability property: overall, 25 out of the 27 systems provide high dynamic support to different patient weights and groups. Two different strategies were used to achieve the dynamic properties in these systems, active dynamic and passive elastic mechanisms. The more common active dynamic is a suspension mechanism that controls the dynamic weight using a force feedback, e.g. Lokolift found in Lokomat [110], whereas the amount of unloaded weight is adjusted in the passive elastic mechanism by changing the springs displacement using an electrical motor, e.g. Lokoiran [74]. Two systems showed a low dynamic property, specifically WHERE-I and UoA PMAbot, due to the use of powerless BWS.

Back-drivability property: most systems presented medium to good back-drivability either for BWS, reciprocal stepping or pelvis robotic modules. In addition, some systems obtained a better score because they used pneumatic actuators, expect LOPES II in which the back-drivability was achieved by a light innovative parallel mechanical configuration.

Free movement property: For BWS, STRING-MAN provided the best free movement since it used six driven cables, which provide 6 DOF. The medium performance class used BWSs and provided good results because of the absence of a suspension harness, which allowed free movement of the trunk. For reciprocal stepping mechanism, all footplate-based devices allowed free upper extremities movement because of the absence of any intersection area. In addition, two systems scored highly for free movement as they utilized an exoskeleton, the parts of which were placed on the patient's back.

DOF/ROM property: for reciprocal stepping mechanism, 74% of systems scored between medium and high, with no maximal scores since no system presented a full DOF and ROM. Most defects were due to lack of ankle joint control and assistance to abduction/adduction of the hip. The dynamic trajectory footplate-based devices had more promising mechanisms because of their abilities to assist the movement of three different joints (hip, knee, and ankle), and to provide an appropriate stride width. Similarly, two over ground systems also scored highly for their abilities to assist for the same three mentioned joints using wearable exoskeletons.

The two versions of LOPES showed the most important treadmill-based devices reciprocal stepping mechanism. An exoskeleton was developed, not only for assisting movement in the sagittal plan, but also for allowing left and right stepping. This was realized by motorized hip ab/ad. The rest of treadmill devices and elliptical footplate devices had low-quality mechanisms mainly due to the constraints and limitations in ROM.

The remaining 26% of the systems had very low scores due to the absence of reciprocal mechanisms, only receiving a score for free movement of the lower limb extremities. It was evident that most systems (about 72%) were over ground based devices because they were developed for assisting patients in later

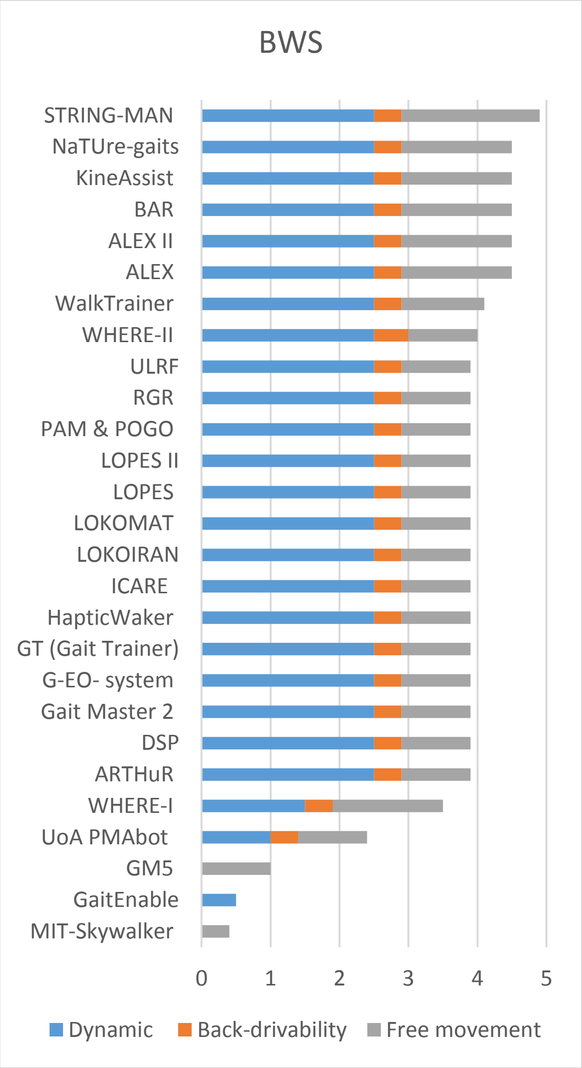

Figure 5.1 Assessment based on BWS evaluation

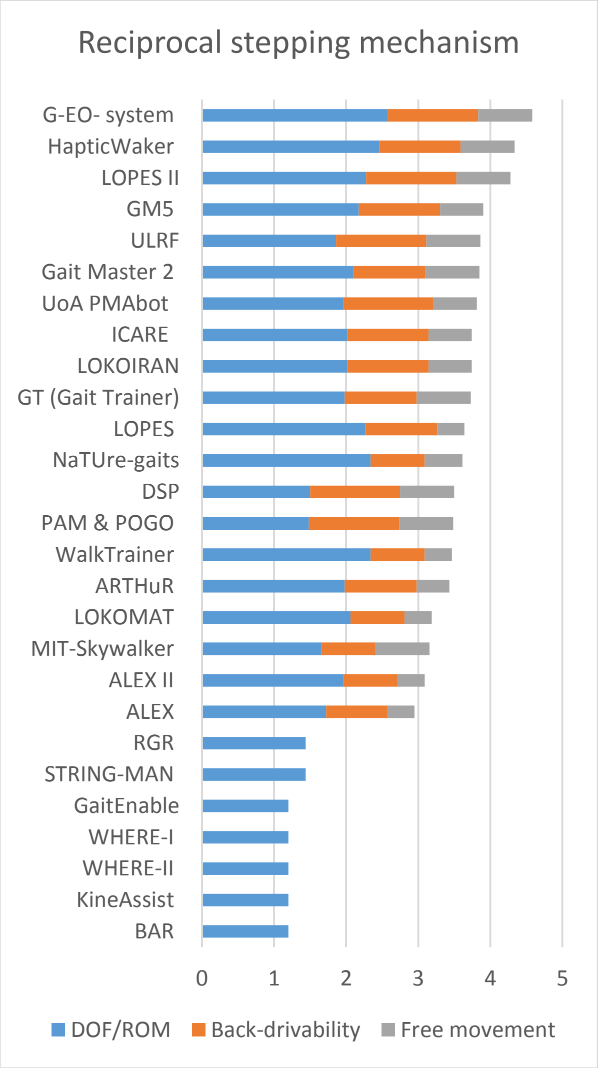

Figure 5.2. Assessment based on reciprocal stepping mechanisms evaluation

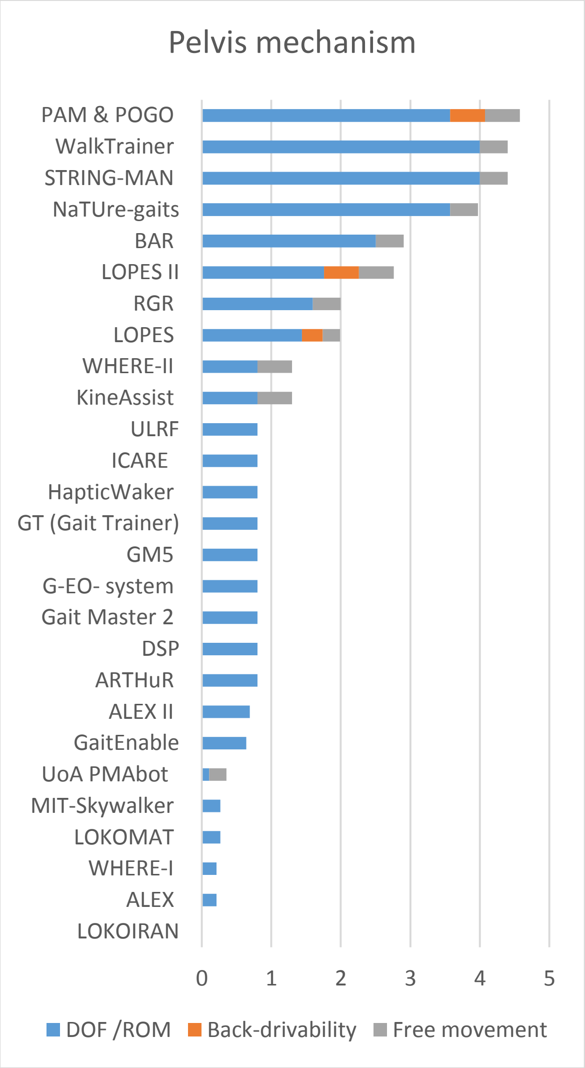

Figure 5.3. Assessment based on pelvis mechanisms evaluation

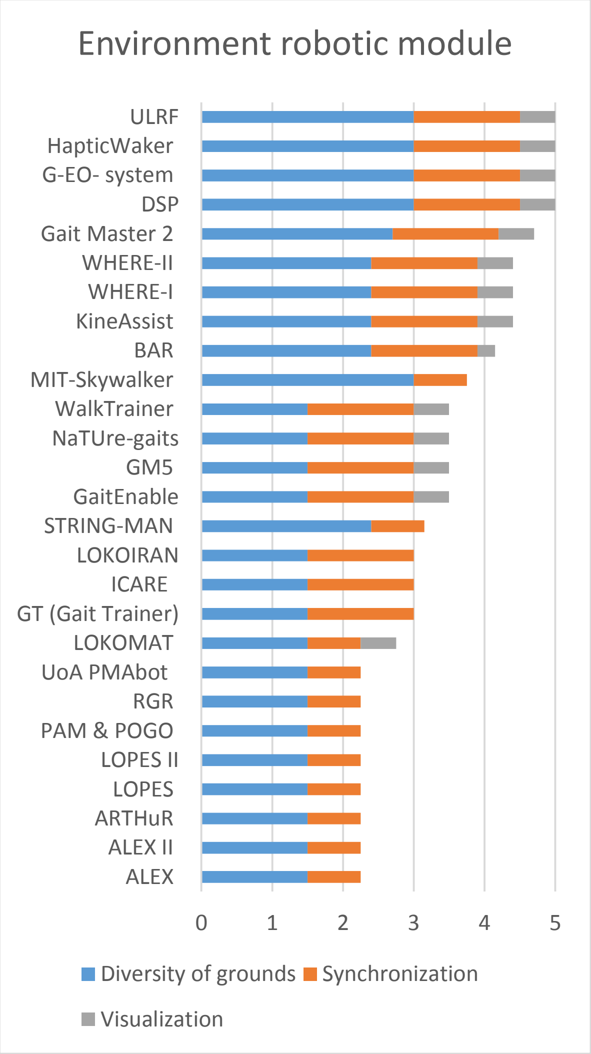

Figure 5.4. Assessment based on environment modules evaluation

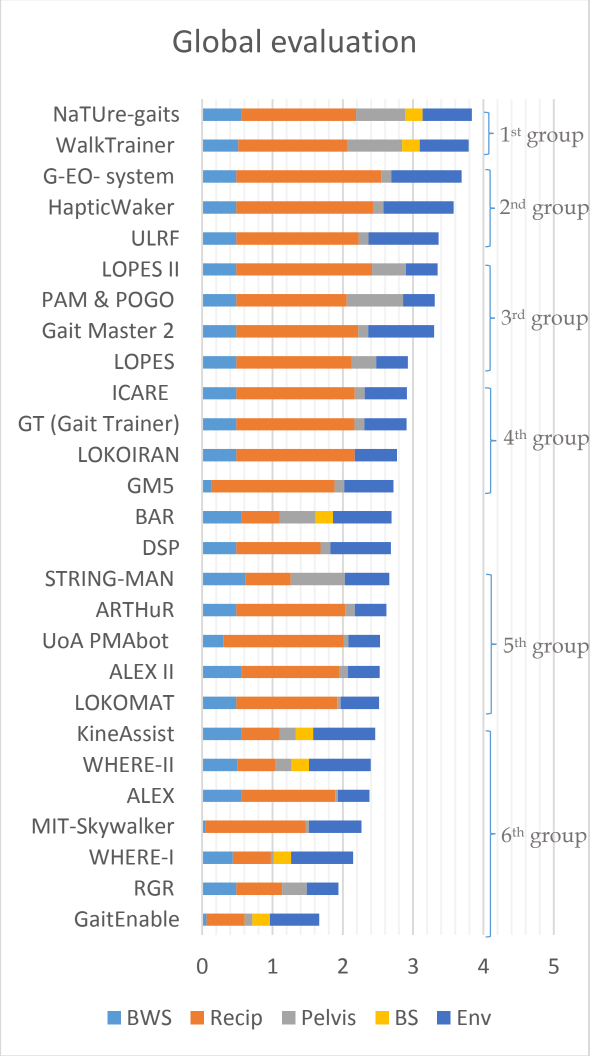

Figure 6. Global evaluation (Recip: reciprocal stepping mechanism, Pelvis: pelvis mechanism, Env: environment robotic module, BW: body weight shifting

recovery stages, where the focus is more on promoting balance. For the pelvis mechanism, 15% of systems obtained a high score for DOF/ROM property. Among them, two systems (NaTUre-gaits and WalkTrainer) had maximum scores because they offered mechanisms assisting the 6 DOF pelvis of motion with full ROM. Also, 15% of systems obtained a medium score, as 3 DOF pelvis movements were assisted, mostly L/R, F/B, and PR movements. Approximately 40% of systems obtained a low score. Most of these systems were footplate-based devices in which there was no pelvis mechanism. However, they obtained a basic score because they allowed free movement. The remaining 30% of systems had a very low score, as they provided no assistance to the pelvis. Moreover, they restricted some important movements.

Environment module

Diversity of grounds: dynamic footplate-based devices scored highly because of the simulation of different training grounds. Applying forces on both feet and controlling the impedance, facilitated training the patient, not only to climb the stair, but also to stumble, thereby improving balance. Twenty-five systems got a medium score, most of which were over ground systems. They offered the possibility to train patient for challengeable exercises such as actual fall experience. Overall, 59% of systems only simulated one type of ground, except for GMT5 that was designed for climbing stairs, the rest simply simulated flat ground. It is important to note that most systems were treadmill-based devices.

Synchronization property: 67% of the systems provided a clear stepping for a real sensation of the actual world. Of the 33% of systems that did not, most were treadmill-based devices, in which there was a shift of speed between the treadmill belt and the foot, resulting in foot drag, except for Mit-Skywalker where this was overcome by two rotational treadmills for each foot.

Visualization property: approximately 48% of systems did not provide any type of visual representation. Most of these systems were treadmill-based devices and fixed trajectory footplate-based devices, in which patients may be confused since there is no correspondence between the movement performed and the scenes.

2) *GLOBAL EVALUATION ANALYSIS*

The global evaluation revealed a mediocre performance for robotic rehabilitation, with the outcome distribution heavily dependent on differences in mechanical design groups. The analyses differentiated six groups, from top to bottom:

- 1st group (2 systems): an excellent score was given to two of the over ground systems NaTUre-gaits and WalkTrainer. This was achieved by an excellent score in BWS and pelvis mechanism, as well as the assistance for body weight shifting. In addition, good reciprocal stepping and environment mechanisms were presented. These 2 systems are designed to assisted a large groups of patients.
- 2nd group (3 systems): a high score was achieved by the dynamic trajectory footplate-based devices groups, due to the development of sophisticated environment robotic modules allowing the simulation of simple and complex grounds. In addition, there were good results for the reciprocal stepping and BWS robotic modules. These systems are mostly designed for assisting patients in intermediate and advanced stage of recovery.
- 3rd group (4 systems): this group of five gait systems mostly included advanced robots of treadmill-based devices. In these systems, a medium to high score was achieved by the reciprocal stepping and pelvis robotic modules, good scoring BWS system and low-quality environment module. These systems are designed mostly for patients in earlier stage of recovery.
- 4th group (4 systems): the three fixed trajectory footplate-based devices performed satisfactorily, with a good BWS, a medium score for reciprocal stepping mechanism and low-quality pelvis and environment robotic modules. These systems are designed mostly for patients in intermediate stage of recovery
- 5th group (5 systems): From STRING-MAN to Lokomat. This group of systems consisted only of treadmill-based devices. Except for the good BWS systems, this group had low score in the folowing robotic modules (reciprocal stepping mechanism, pelvis mechanism and enviroment). Most of these systems are developed for assisting patients in earlier stage of recovery.
- 6th group: the rest of the 26% systems were considered having low score in almost each robotic module. This group included a mix of treadmill and over ground systems, with very low-quality BWS, reciprocal stepping and pelvis mechanisms being their most important characteristics. These robots are designed for assisting patients in advanced stage of recovery.

VI. CONCLUSION

According to our method to compare rehabilitation systems, the simulation of the ground seems important for better outcomes (only four of the gait systems identified in this study were able to support more advanced training of daily activities). While some commercialized systems still commonly used (e.g., Lokomat) are outdated and do not adopt a comprehensive strategy, some prototypes are very interesting (e.g., NaTUre-gaits), but as they are not commercialized, their safety, efficiency and efficacy have not yet been confirmed. Furthermore, optimal rehabilitation systems should focus on many aspects rather than one specific task. In addition, it is recommended that further research in gait robotic design is conducted to enhance the properties of pelvis mechanisms as this robotic module had a poor average score compared to the other modules.

The evaluation of the different characteristics and weights of the features was challenging due to the lack of quantitative data, probably due to the absence of standards that show quantitatively the importance of features within the different stages. Therefore, we call for a review of these standards, the addition of more, as well as new methods for evaluation. This could be achieved by collating the results from different studies already conducted, as well as conducting specific studies evaluating the needs of patients according to the stage and the

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importance of each feature of the stage.

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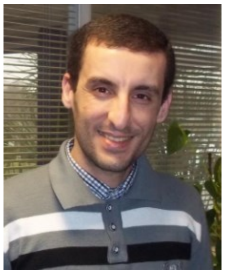

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