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Pelvis mobility control solutions for gait rehabilitation systems: a review

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Abstract
Pelvis mobility plays a big role during normal walking. There are six pelvic movements that allow natural gait patterns and center of mass trajectories. The pelvis mechanism is an underdeveloped component in gait rehabilitation systems. Mobility constraints and human-robot joint misalignment appear during gait if pelvis motion is restricted or not actuated. This is why systems should provide pelvis mobility control.

The aim of this review is to help researchers identify weaknesses and come up with solutions for new generations of gait rehabilitation devices.

The data on current gait systems with pelvic mechanisms was collected from various databases on 26 August 2020. The selection criteria included all devices that had at least one pelvic degree of freedom actuated by a pelvis mechanism and excluded all devices with all pelvic degrees of freedom passive or restricted and all devices with pelvic support only for registering data and not for controlling pelvic motion.

A number of 16 devices were identified. Different characteristics are compared, including: the type of system, the system mechanical components, the type of surface, the pelvic robot – human interface, the allowed human pelvis movements and the types of pelvic movements (actuated, free or blocked), the pelvis actuation, the operating modes and the center of mass trajectory.

There is no perfect system; each one of them has both strong and weak points. Research directions are suggested for system improvements that might help future gait rehabilitation devices.
Keywords: pelvis mechanism, pelvic movement, gait rehabilitation, overground, exoskeleton.

Introduction

The requirements needed for walking are: a) neurological, such as equilibrium and trunk stability (the ability to assume the upright position and maintain balance); b) locomotion related (the ability to initiate and maintain rhythmic stepping); c) non-neurological, such as good range of motion and efficacious muscles (Giladi et al., 2002; Jung et al., 2018). Walking is impossible if there is no reaction force when touching the ground (Lim et al., 2011).

Saunders et al.'s theory about the six determinants of gait states that mechanisms at knee, foot and hip level, together with pelvic movements are responsible for reducing the vertical movement of the center of mass (CoM) (Saunders et al., 1953). The six determinants are pelvic transverse rotation, pelvic tilt, stance phase knee, flexion, knee mechanisms, foot mechanisms, and lateral displacement of the pelvis. Three out of the six determinants are pelvic motions, which highlight the importance of pelvic control during gait rehabilitation (Lim et al., 2011).

The pelvis is the center of the body weight and the link between the lower limbs and the trunk, and therefore it has an important role in maintaining the trunk in upright position (trunk stability), in maintaining balance and in ensuring the movement of the lower limbs (Torricelli et al., 2016; Ventura et al., 2015).

During walking, there are six pelvic movements described in all three planes (Ayad et al., 2019): 3 translations: mediolateral (left/right); anteroposterior (forward/backward); superior-inferior (up/down) and 3 rotations or angular displacements (Table I).

Table I
Pelvic rotations.

Name	About which axis	In what plane
Transverse rotation (internal-external rotation)	Vertical	Transverse (horizontal)
Tilt (antero-posterior rotation)	Transverse (medio-lateral)	Sagittal (longitudinal)
Obliquity (up-down rotation)	Sagittal	Coronal (frontal)

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The frequency, amplitude and mean position of the pelvic oscillations during walking depend on the following parameters: walking speed, stride length and step rate (Ijspeert, 2014; Lim et al., 2011; Torricelli et al., 2016). Therefore, pelvic motion adaptation is required when an external intervention changes these gait parameters (Vashista, 2015).

When walking at natural speeds, the CoM follows an undulating path with amplitudes of about 5 cm in the mediolateral and vertical directions. In addition, pelvic mediolateral displacement allows weight shift towards the stance foot, moving the CoM above this leg (Vashista, 2015). The CoM path in the sagittal plane is determined by: hip flexion, stance knee flexion, and ankle-foot interaction (composed of ankle plantar flexion, toe flexion and the displacement of the center of pressure). In the coronal plane, the mediolateral path of the CoM is determined by hip adduction and pelvic tilt. The vertical path of the CoM is determined by pelvic rotation and pelvic tilt (Lin et al., 2014).

Pelvic motion influences balance during walking due to the proximity to the body's CoM (Endo & Herr, 2014). For example, the vertical motion of the pelvis enables the vertical displacement of the CoM. This enables the exchange of gravitational potential and kinetic energy during walking (Gonzalez-Vargas et al., 2015). Pelvic motion allows the transfer of forces from the lower extremity to the trunk, and thus helps in the forward propulsion of the body (Lim et al., 2011). Inertia or mobility constraints produce changes in the pelvic motion and require adaptation of lower limb motion (Vashista, 2015).

The most important modules a system should have are: body weight support (BWS) subsystem, reciprocal stepping mechanism (or cyclical leg movement mechanism), body weight shifting module, pelvis mechanism (or pelvis motor unit) and environmental module (Ayad et al., 2019).

The priorities of the development of systems are usually the higher number of degrees of freedom (DoFs) and the wide range of motion. Lightweight and high dynamic driving mechanism are taken less into consideration and free movement has the lowest priority (Ayad et al., 2019).

Another underdeveloped component is the pelvis mechanism. It is necessary to develop multi-DoF pelvis mechanisms that provide assistive force field to the pelvis and permit natural pelvis movement during gait training (Olenšek et al., 2016). If the system does not provide control of all six DoFs of the pelvis, then mobility constraints and human-robot joint misalignment occur during gait (Vashista et al., 2016). Unconstrained pelvis movement is essential for assessing balance during walking. Gait characteristics are changed when the pelvis is fixated and its DoFs reduced. This can lead to improper execution of balance responses (Olenšek et al., 2016). The restrictions of the pelvic movements also affect the joints of the legs and lead to abnormal gait patterns (Jung et al., 2018).

There are different approaches that have been proposed to address these needs, but further research is needed (Olenšek et al., 2016). The means of evaluating the pelvis mechanism are: DoF, range of motion, backdrivability and free movement (Ayad et al., 2019).

Gait Rehabilitation Systems Identification

This review focuses on gait rehabilitation systems that have pelvic mechanisms. The aim of the review is to help researchers identify weaknesses and come up with solutions for new generations of gait rehabilitation devices.

Identification of systems:

The data on current gait systems with pelvic mechanisms was collected on 26 August 2020 from the following databases: PubMed, IEEE Xplore, ResearchGate and Web of Science. The search terms used were:

((robot*) OR (robot-assisted) OR (exoskeleton) OR (orthosis) OR (end-effector) OR (treadmill) OR (overground) OR (over ground) OR (system) OR (device) OR (manipulator)) AND ((gait*) OR (walk*) OR (locomotion)) AND ((pelvic motion) OR (pelvic translation) OR (pelvic rotation) OR (pelvic tilt) OR (pelvic obliquity) OR (pelvic mechanism) OR (pelvic module) OR (pelvic subsystem) OR (pelvic driven) OR (pelvic unit) OR (pelvic device) OR (pelvic support*) OR (pelvic control) OR (pelvis control) OR (pelvic assist*))

ScienceDirect and Scopus were omitted because the search engine does not support so many Boolean connectors. The "*" sign was used to replace all derived words (e.g. robotic for robot*).

Inclusion criteria:

All devices that have at least one pelvic DoF actuated by a pelvis mechanism.

Exclusion criteria:

All devices with all pelvic DoFs passive or restricted; devices with pelvic support only for registering data and not for controlling pelvic motion.

Selection:

The first 100 articles (sorted by relevance/best match) from each database search results were taken into consideration and 16 devices were identified. If a system had more versions/prototypes, the latest one to meet the criteria was chosen.

Gait Rehabilitation Systems Characteristics

The characteristics of the 16 identified devices are shown in Tables II-VII. The order in which the systems are presented is random.

The names of the systems are included in Table II along with their general characteristics: i) type of system; ii) mechanical components of the system and whether it has a BWS subsystem or not; iii) whether the system has an intention recognition subsystem or not; iv) over what type of surface the user can walk; v) the type of robot-human interface the system has at pelvic level; vi) the years of first and latest research papers found regarding the system. In order to find the date of the research papers, the name of each system was searched again in the same databases.

Table III offers information on the movements the human pelvis can make while using each system. Table IV gives information about the actuation of the system's mechanical parts that enable human pelvis movements, while Table V describes whether the movement is actuated, passive or blocked. Table VI offers information on the operating modes under which the systems can perform and Table VII whether the systems affect the CoM trajectory or not.

No information was obtained in what concerns the range of motion that the pelvis mechanism provides for any of the movements, with one exception: the Lokomat Pro (Table III).

Table II
Systems with pelvic mechanism.

System /Name	Type of system	System mechanical components		Intention recognition control subsystem		Type of surface	Pelvic robot-human interface	Year of first research paper	Year of latest research paper
		BWS[1] system	Others	FES[2]	Others				
Lopes II Alingh et al. (2019); Meuleman et al. (2016); Ekkelenkamp et al. (2007); Veneman (2007); Veneman et al. (2007)	Exoskeleton	Yes (cBWS[3])	Exoskeleton Treadmill	No	No	Treadmill	Harness	2016	2019
PAM (Pelvic Assist Manipulator) Aoyagi et al. (2007); Ichinose et al. (2003)	Pelvic manipulator	Yes (cBWS)	2 pneumatic robots Treadmill	No	No	Treadmill	Pelvic belt	2003	2007
NaTUre-Gaits II (Natural and Tunable Rehabilitation Gait System) Lim at al. (2011); Trieu Phat Luu et al. (2014)	Overground	Yes (sBWS[4] integrated in the PA pelvis mechanism + cBWS)	Pelvic Assistance (PA) Mechanism Mobile Platform Robotic Orthosis	No	No	Flat	Contact surface at hip joint with the end effectors	2011	2014
Stand Trainer[5] Khan et al. (2018)	Cable-driven robot	Cable-driven pelvic robot which can support the body weight of the user Force plates		No	No	Force plates or treadmill	Pelvic and trunk belts on which cables are attached	2018	2018
WalkTrainer Stauffer et al. (2009); Stauffer et al. (2008); Stauffer et al. (2007); Yves et al. (2010)	Overground	Yes (cBWS)	Leg orthosis Pelvic orthosis Muscle stimulator Deambulator (the frame)	Yes (CLEMS[6])	No	Flat	Belt + Pelvic rigid orthosis	2007	2010
Lokomat Pro Aurich-Schuler et al. (2019a); Aurich-Schuler et al. (2019b); Aurich-Schuler et al. (2017)	Exoskeleton	Yes (cBWS)	Exoskeleton FreeD module Treadmill	No	No	Treadmill	Harness + Back pelvis contact	2017	2019
ALEX III (Active Leg Exoskeletons) Stegall et al. (2017); Zanotto et al. (2014); Zanotto et al. (2013)	Exoskeleton	No	Exoskeleton Support platform Treadmill	No	No	Treadmill	Belt + Pelvic rigid frame	2013	2017
RGR Trainer (Robotic Gait Rehabilitation Trainer) Pietrusinski et al. (2014); Pietrusinski et al. (2012); Pietrusinski et al. (2010a); Pietrusinski et al. (2010b)	Exoskeleton	No	Exoskeleton Treadmill Stationary frame	No	No	Treadmill	Pelvic brace	2010	2014
JARoW-II (JAIST Active Robotic Walker) Ohnuma et al. (2017)	Overground	No	Upper frame with pelvis mechanism and base frame with omni-wheels unit	No	No	Flat	Pelvic brace	2017	2017
IBWS (Ischiatic body weight support system) (Salgcuero-Beltrán et al.(2012)	Assistive manipulator	Yes (sBWS integrated in the pelvis mechanism)	Assistive manipulator Treadmill	No	No	Treadmill	Pelvic socket	2012	2012
COWALK Jung et al. (2018); Jung et al. (2014)	Exoskeleton	Yes (cBWS)	Exoskeleton leg unit Gravity compensation unit Pelvis motion unit Treadmill	No	No	Treadmill	Pelvic brace	2014	2018
AssistOn-Gait Munawar et al. (2015; Munawar et al. (2016)	Overground	Yes (cBWS)	Mobile base Pelvis-hip exoskeleton	No	No	Flat	Harness with back support	2015	2016
Gait Rehabilitation Robot Liu et al. (2016); Watanabe et al. (2010)	Pelvic manipulator	Yes (sBWS integrated in the pelvis mechanism for PBWS[7])	Split treadmill Pelvic support manipulator Visual interface	No	No	Treadmill	Pelvic frame	2010	2016
Lower Limb Rehabilitation Robot Shi et al. (2014)	Exoskeleton	Yes (sBWS integrated in the pelvis mechanism)	Exoskeleton Walker Treadmill	No	No	Treadmill	Back pelvis and back trunk contact	2014	2014
String-man (Surdilovic et al., 2007; 2004)	Wire-robot	Wires for PBWS and for controlling posture Treadmill		No	No	Treadmill	Harness (corsage)	2004	2007
TPMAD (Trunk and Pelvis Motion Assistance Device) Hashimoto et al. (2018)	Hip and chest orthosis	No	Hip mount Chest mount Flexible shaft between them	No	No	Any	Hip mount	2018	2018

[1]BWS = body weight support, [2]FES = functional electric stimulation, [3]cBWS = cable harness BWS, [4]sBWS = structural harness BWS, [5]Stand Trainer is the upgraded version of A-TPAD, (Active Tethered Pelvic Assist Device) and TruST (Trunk Support Trainer), [6]CLEMS = Closed loop electrical muscle stimulation, [7]PBWS = partial body weight support

Table III
Allowed human pelvis movements.

System Name	Human pelvis movements allowed	
	Translations	**Rotations**
Lopes II	All three	All three
PAM	All three	All three
NaTUre-Gaits II	All three	All three
Stand Trainer	All three	All three
WalkTrainer	All three	All three
Lokomat Pro	Medio-lateral translation up to 4 cm (per side) Vertical translation	Transverse rotation up to [4]O
ALEX III	All three	Transverse rotation Obliquity
RGR Trainer	All three	All three
JARoW-II	All three	All three
IBWS	All three	All three
COWALK	All three	Transverse rotation
AssistOn-Gait	All three	Transverse rotation Tilt
Gait Rehabilitation Robot	Medio-lateral translation Vertical translation	Transverse rotation
Lower Limb Rehabilitation Robot	Medio-lateral translation Vertical translation N/A for the antero-posterior translation and for the rotations	
String-man	All three	All three
TPMAD	All three	All three

Table IV
Pelvis actuation.

System Name	System actuated DoFs[1] for pelvis movements			Type of actuators that enable pelvis movements
	Total actuated DoFs	**Pelvis mechanism actuated DoFs**	**Other subsystems that provide actuated DoFs**	
Lopes II	3	2	1 (BWS system)	Linear actuator for forward direction (max. force 200N) SEA[2] for the sideways direction (max. force 200N)
PAM	5	5		2 x 3 pneumatic cylinders
NaTUre-Gaits II	5	4 (2x2 robotic arms) + 1 (lateral shift mechanism)		DC[3] brushless motors
Stand Trainer	Customizable (up to 6 DOF)	Customizable (up to 6 DOF)		14 DC motors
WalkTrainer	6	6		DC motors
Lokomat Pro	N/A	N/A	N/A	N/A
ALEX III	4	4		Permanent magnet brushless motors
RGR Trainer	1	1		Servo-tube linear electromagnetic actuator
JARoW-II	3	2	1 (omni-wheels unit of the base frame)	3 AC[4] servomotors 1 brushless DC motor
IBWS	5	5		2 rotary motors 1 linear motor
COWALK	3	3		3 linear actuators (brushless DC motors)
AssistOn-Gait	5	4	1 (BWS system)	SEA
Gait Rehabilitation Robot	3	3		Brushless DC motor
Lower Limb Rehabilitation Robot	2	1	1 (exoskeleton)	Linear actuator DC motor
String-man	6			DC motors
TPMAD	1	1		Maxon Motor

[1]DoF = degree of freedom, [2]SEA = series elastic actuator, [3]DC = direct current, [4]AC = alternative current

Table V

Types of pelvic movements provided by the systems.

System Name	Actuated/Active Movements		Free/Passive Movements		Blocked/Restricted Movements	
	Translation	**Rotation**	**Translation**	**Rotation**	**Translation**	**Rotation**
Lopes II	Medio-lateral Antero posterior		Vertical	Transverse rotation Obliquity Tilt		
PAM	All three	Transverse rotation Obliquity		Tilt		
NaTUre-Gaits II	All three	All three				
Stand Trainer	All three	All three				
WalkTrainer	All three	All three				
Lokomat Pro	Medio-lateral	Transverse rotation	Vertical		Antero-posterior	Tilt Obliquity
ALEX III	All three	Transverse rotation		Obliquity		Tilt
RGR Trainer		Obliquity	All three	Tilt Transverse rotation		
JARoW-II	Medio-lateral Antero posterior	Transverse rotation Tilt	Vertical	Obliquity		
IBWS	All three	Transverse rotation Obliquity		Tilt		
COWALK	Medio-lateral Antero posterior	Transverse rotation	Vertical			Tilt Obliquity
AssistOn-Gait	All three	Transverse rotation Tilt (when not coupled with the mobile base)		Tilt (when coupled with the mobile base)		Obliquity
Gait Rehabilitation Robot	Medio-lateral Vertical	Transverse rotation			Antero-posterior	Tilt Obliquity
Lower Limb Rehabilitation Robot	Medio-lateral Vertical			N/A		
String-man	All three	All three				
TPMAD		Transverse rotation	All three	Tilt Obliquity		

Table VI

Operating modes.

System name	Active (Assistive) Mode		Passive (Non-Assistive) Mode*		Back drivable
	System follows patient and intervenes only if needed	**System follows patient and intervenes throughout the training**	**System is in control and the patient is passively mobilized by the system**	**System follows patient, but does not intervene and the patient moves freely**	
Lopes II			Yes - "Robot in charge" and "Therapist in charge" (selected torques can be applied)	Yes - transparent mode ("Patient in charge")	Yes
PAM			Yes	Yes	Yes
NaTUre-Gaits II			Yes		No
Stand Trainer		Yes		Yes	Yes
WalkTrainer			Yes		No
Lokomat Pro	Yes – "Path control" mode. The system intervenes only if the patient's leg trajectory is outside the virtual torque field tunnel	Yes - "Guidance Force" mode between 0 and 100%	Yes - "Guidance Force" mode at 100%	Yes - "Guidance Force" mode at 0	Yes
ALEX III		Yes - "Assistive/Resistive" mode (variable interaction)	Yes - "Locked" mode (infinite stiffness)	Yes - transparent mode (zero-interaction)	Yes
RGR Trainer			Yes - system in control, during hemiparetic leg swing	Yes - the system is transparent during hemiparetic leg stance phase and healthy leg swing	Yes
JARoW-II		Yes		Yes	Yes
IBWS			Yes		No
COWALK		Actuated legs and actuated pelvis mode	Actuated legs and locked pelvis mode	Free walking mode	Yes
AssistOn-Gait		Yes		Yes	Yes
Gait Rehabilitation Robot			Yes	Yes	Yes
Lower Limb Rehabilitation Robot			Yes	Yes - the system has a device for following the center of gravity	Yes
String-man		Yes		Yes	Yes
TPMAD		Yes			No

Table VII
Center of mass trajectory.

System Name	CoM[1] trajectory of subjects
Lopes II	Allows natural accelerations of the CoM in the vertical axis
PAM	Allows the recording of pelvis movements and has achieved synchronization under the teach-and-replay scheme of normal gait patterns, and therefore CoM trajectories
NaTUre-Gaits	No studies yet, but affects ground reaction forces
Stand Trainer	CoM control (decrease in pelvic oscillations and decrease in CoP trajectory excursions) in static and dynamic conditions
WalkTrainer	Overall reduction of the motion of CoM
Lokomat Pro	Unnatural due to the restricted motions of the pelvis
ALEX III	Unnatural due to the restricted tilt rotation of the pelvis
RGR Trainer	N/A
JARoW-II	Allows 3D movement of the CoM
IBWS	No studies yet, but reduced ground reaction forces
COWALK	Enables control of the patient's CoM
AssistOn-Gait	N/A
Gait Rehabilitation Robot	N/A
Lower Limb Rehabilitation Robot	Control of CoM in the vertical axis
String-man	N/A
TPMAD	N/A

[1]CoM = center of mass

Gait Rehabilitation Systems Analysis

Type of system, system mechanical components and type of surface

Overground systems and exoskeletons are the most common types of systems that can offer a pelvic mechanism.

Overground systems use the flat surface of the environment (e.g.: room) to train patients, which can lead to a couple of advantages. They are suitable for training of turning manoeuvres, a development that is highly necessary (Pavčič et al., 2014) to avoid obstacles. Also, fall experiments can be performed or exercises on unstable grounds that teach balance (Wang et al., 2011). Applying unexpected perturbations helps study the motor responses of the central nervous system in order to restore balance and prevent fall (Olenšek et al., 2016). All of these trainings and experiments require good control of pelvis motion and of the CoM.

NaTUre-Gaits II, WalkTrainer, JARoW-II and AssistOn-Gait are overground systems that use a mobile base or platform for walking on flat surfaces. Out of the four systems, only JARoW-II does not have a robotic lower limb orthosis or exoskeleton.

With the exoskeleton systems, natural gait patterns can be achieved by using a high number of actuated DoFs. This, however, requires many mechanical parts, which rises the complexity of the mechanism and thus the cost and the weight of the system (Novandy et al., 2009). The heavier the exoskeleton is, the more discomfort the patient feels and the more abnormal the gait patterns become. This vicious cycle results in unsuccessful recovery (Jezernik et al., 2004) if solutions are not found.

Lopes II, Lokomat Pro, ALEX III, RGR Trainer, COWALK and Lower Limb Rehabilitation Robot are treadmill-based exoskeletons that actuate pelvis movements. Lopes II has come up with a solution in respect to the weight problem of exoskeletons. The mechanical part and the actuators are located in a unit behind the patient called "shadow leg" and the patient is connected to this unit with clamps. This way, the patient does not bear the weight of the exoskeleton. Lokomat Pro, ALEX III, COWALK and Lower Limb Rehabilitation Robot, on the other hand, support the entire weight of the exoskeleton with the help of mechanical arms attached to a fixed unit located behind the patient. RGR Trainer's actuation system is gravity compensated as well.

Treadmill-based exoskeletons usually restrict pelvic motions. This can lead to less satisfactory functional outcomes (Guo et al., 2014). Such exoskeletons are Lokomat Pro, Alex III and COWALK. The blocked pelvis movements are described in Table V.

Other treadmill-based systems with pelvis mechanism are pelvic manipulators (such as PAM, IBWS and Gait Rehabilitation Robot) and cable-driven robots or wire-robots (Stand Trainer, which can also work with force plates and String-man).

In the literature there is a debate on the similarity of treadmill walking vs. overground walking. Some studies show that treadmill walking produces different kinematics, while other studies show that treadmill and overground walking produce equal kinematics (Olenšek et al., 2016).

Treadmill-based and footplate-based systems are static. The ground moves under the patient's feet, which is a different stimulation from normal walking. The stimulation of the ground seems indispensable for better outcomes. Overground devices are movable systems. The patient interacts with and travels directly on real ground (Ayad et al., 2019). Although NaTUre-Gaits II is an overground system, it has metallic foot plates between foot and ground and does not allow ground stimulation.

The complexity of overground systems can rise by adding different ground textures or stairs so that the patient can train going up and down (Ayad et al., 2017). All overground systems selected in this review have a mobile base, which limits the training on stairs and some ground textures.

The last system is TPMAD, which is a hip and chest orthosis that can be worn by the patient on any type of surface.

There are two BWS concepts in the literature: the cable-harness BWS (cBWS) concept, when the user wears a harness system, and the structural BWS (sBWS) concept, when the user's BWS is held by a robotic mechanism at waist or back level (Lim et al., 2010). cBWS systems are attached to the suspension mechanism through one single point. This results in lack of control over the direction of the harness when the user tries to walk. However, this can be compensated by the use of a pelvic frame (Mikolajczyk et al., 2018). All the systems in this review have a pelvic mechanism and therefore a degree of control over the direction of the harness.

There are 4 devices out of 16 (ALEX III, RGR Trainer, JARoW-II and TPMAD) that do not have a BWS system and 2 are cable/wire driven robots (Stand Trainer and String-man), meaning that cables can be used to support the body weight of the user. The rest of the systems have either cBWS systems (Lopes II, PAM, WalkTrainer, Lokomat Pro, COWALK and AssistOn-Gait) or sBWS systems (IBWS, Gait Rehabilitation Robot, Lower Limb Rehabilitation Robot). NaTUre-Gaits II is equipped with both sBWS and cBWS systems.

Intention recognition control subsystem and controlled electro-induced contractions

Only one system out of the 16 identified has an intention recognition subsystem. WalkTrainer has a closed-loop FES incorporated, named CLEMS (closed loop electrical muscle stimulation), which targets the main muscles responsible for gait: Gluteus Maximus, Vastus Medialis, Vastus Lateralis, Rectus Femoris, Hamstrings, Tibialis Anterior and Gastrocnemius. When the patient tries to move the leg, CLEMS detects the proprioceptive impulses generated by the Golgi apparatus and the neuromuscular spindles of the muscular-tendinous system (Métrailler et al., 2007). Unlike classical FES, which is opened-loop and cannot adapt the stimulation intensity during the execution of movement, CLEMS can, having force sensors placed on the exoskeleton leg, which maximizes the chances for recovery (Stauffer et al., 2009; Métrailler et al., 2007). The force sensors can measure the force and determine the amplitude and position of lower limb segments and therefore, adjust and control the contraction intensity (Stauffer et al., 2009).

Pelvic robot-human interface

The most common pelvic robot-human interface is a pelvic harness, brace or belt, which is in contact with end effectors that provide active movement of the pelvis. For cable or wire driven robots, the interface is represented by either a harness or pelvic and trunk belts on which the cables are attached.

The IBWS has a pelvic socket. In order to firmly fit and attach to the user's particular anatomy, it is designed with six adjustment degrees (Salguero-Beltrán et al., 2012) Although it allows stable body posture with free movement of arms and legs, its structure is rigid (Salguero-Beltrán et al., 2012) and might create discomfort when walking.

Another notable aspect is that there is no perfect harness. All of them induce focal pressure and restrict functional normal gait movements (Mikolajczyk et al., 2018).

Years of first and latest research papers

Two of the systems (PAM and String-man) have their latest research in 2007, which might mean they are discontinued. On the other hand, the most recent researches are on Lopes II and Lokomat Pro (2019), Stand Trainer, COWALK and TPMAD (2018). The rest of the systems might be waiting for finance for upgrades and future research. The most researched system (the number of years spent in research) is Gait Rehabilitation Robot (6 years), followed by Lopes II, PAM, ALEX III, RGR Trainer and COWALK (4 years), while some devices were studied only 1 year (Stand Trainer, JARow-II, IBWS, Lower Limb Rehabilitation Robot and TPMAD).

Allowed human pelvis movements, types of pelvic movements and center of mass trajectory

A number of 6 systems do not allow all six movements of the user's pelvis (Tables III, V). Lokomat Pro and Gait Rehabilitation Robot allow only 3 motions: (mediolateral translation, vertical translation and transverse rotation), the rest of them being restricted. COWALK has tilt and obliquity restricted, while ALEX III and AssistOn-Gait have only one restricted motion: tilt and obliquity, respectively.

There are 4 systems (Lokomat Pro, ALEX III, COWALK, Gait Rehabilitation Robot) which have the most important pelvic motions (lateral translation, transverse rotation and tilt) restricted, while only NaTUre-Gaits II, Stand Trainer and WalkTrainer provide actuation for all 6 movements of the pelvis.

Lopes II, PAM, RGR Trainer JARoW-II, IBWS, String-man and TPMAD actuate some motions, while the rest of them are passive or free. RGR Trainer and TPMAD provide only one active movement, the rest of them being free, and Lopes II and Lokomat Pro provide only 2 active movements.

The trajectory of the center of mass (Table VII) is strongly influenced by the restricted motions and also by the free movements of the pelvis if the user has gait dysfunctions. Therefore, theoretically, only NaTUre-Gaits II, Stand Trainer and WalkTrainer are capable of providing the most natural CoM trajectories. However, NaTUre-Gaits II is known to affect the ground reaction forces and therefore it might influence the CoM trajectory as well.

Lopes II, PAM, JARoW-II, COWALK and Lower Limb Rehabilitation Robot partially provide the control of CoM, by reducing the trajectory excursions in some axis.

Pelvis actuation

Traditionally, the interface between an actuator and its load was stiff. The advantages for reducing the interface stiffness are lower reflected inertia, greater shock tolerance, more stable and accurate force control and the capacity for storing energy. A series elastic actuator (SEA) has an elastic component – a spring – that is able to support loads and is not too stiff (Pratt & Williamson, 1995). These compliant actuators are designed to reproduce the net human joint torque using the spring during specific gait sub-phases (Sartori et al., 2015; Shamaei et al., 2013).

The term quasi-stiffness was introduced to represent the relation between torque and joint angles and it does not reflect the actual stiffness of biological joints (Sartori et al., 2015; Shamaei et al., 2013). Human joint stiffness represents the association of muscle activation and the velocity of its contraction and the elasticity of muscle fibers and tendons (Sartori et al., 2015).

The actuators should reproduce both quasi-stiffness and joint stiffness. The latter is more difficult to obtain due to the complex modulation at muscle and joint level, while quasi-stiffness can be easily measured using inverse dynamics (Sartori et al., 2015).

Compliant actuator technology is still in its early development (Vanderborght et al., 2013). How compliance is modulated and how it influences global stability, it is not yet clear (Qiao & Jindrich, 2016). The answers would help to develop effective systems for gait rehabilitation by reproducing typical gait patterns and corresponding ground reaction forces (Torricelli et al., 2016).

WalkTrainer and String-man have 6 actuated DoFs for pelvis movements, while Stand Trainer is customizable and can provide up to 6 active DoFs. PAM, NaTUre-Gaits II, IBWS and AssistOn-Gait have a total of 5 actuated DoFs. RGR Trainer and TPMAD have only 1 actuated DoF and Lower Limb Rehabilitation System provides only 2 active DoFs (Table IV).

WalkTrainer has selective compliance, which means that the physician can decide what DoFs should be made compliant (Stauffer et al., 2009).

Operating modes

In the early stages of rehabilitation, the patient is unable to move a part or all of the lower limb segments, therefore the system should be able to make the movements for the patient. However, after a period of time, the patient might start recovering motor control and the system must be able to adapt and actively assist the patient. This means the patient should start the movement and the system should adjust the trajectory and control the range of motion (Meuleman et al., 2016).

Backdrivability is used to control the force applied by the system on its user, without using force sensors and implementing a feedback loop. Perfect backdrivability is when the torque is 0 (zero-transparency, with no friction or stiffness involved), which is difficult to achieve, if not impossible. This is why systems that provide high mechanical transparency have high backdrivable actuators, meaning that the mechanical transmission friction and the torques are as close to 0 as possible. This allows the robot to follow the user which moves freely, unconstrained (Gosselin et al., 2016; Koganezawa et al., 2011).

A number of 4 systems are not backdrivable (NaTUre-Gaits II, WalkTrainer, IBWS and TPMAD), and 5 systems (Stand Trainer, JARoW-II, AssistOn-Gait, String-man and TPMAD) do not provide the operating mode in which the robot is in control and the user follows the robot passively. There are 8 systems which are capable of following the patient and intervening throughout the entire training session, even if not needed (Stand Trainer, Lokomat Pro, ALEX III, JARoW-II, COWALK, AssistOn-Gait, String-man and TPMAD), and only one system (Lokomat Pro) has an operating mode in which the robot intervenes only if needed, when the patient's leg trajectory passes outside the virtual torque field tunnel (Table VI).

Conclusions

1. The main objective of the gait rehabilitation systems is to help patients achieve the highest possible level of functional independence, given their situation.

2. Future research directions for system improvements should consider motion intention recognition systems based on brain computer interface, FES, EEG or other technologies that can be applied in a closed biofeedback loop, in order to predict and assist the patients' movements and adjust their trajectory and range of motion only if needed. It would make a huge difference if it can be implemented for assisting the pelvis, as well as the impaired lower limb.

3. Other challenges address the backdrivability and control system that should be able to compensate the device's inertial effects and therefore, synchronize automatically the device's motion with the user's motion.

4. Regarding the harness, although there is no perfect harness, it can be equipped with pressure sensors to establish the degree of pressure and help the patient relieve it, by making adjustments.

5. Future research is needed to conclude whether treadmill kinematics are different from overground kinematics.

6. Future objectives should include the increase of the addressability of these gait rehabilitation systems in order to cover more complex gait disabilities generated by diverse pathologies. This can be achieved by giving up on the mobile base of overground systems and coming up with a better mechanical solution that can enable the patient to train in more complex environments, such as different ground textures or stairs.

Conflicts of interests

Nothing to declare.

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