Preliminary Investigation on the Development of a Lower Extremity Exoskeleton for Gait Rehabilitation: A Clinical Consideration

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***Abstract*—Gait disorder is the inability of one to maintain balance, assume upright position nor the aptitude to initiate and sustain rhythmic stepping. This form of abnormality may originate from cerebellar disease, stroke, spinal injury, cardiac disease or other general conditions that may instigate such disorder. Studies have shown that one's mobility may be improved with continuous locomotor activity. Conventional rehabilitation therapy is deemed too laborious as well as cost demanding. Rehabilitation robotics have been explored to address the drawbacks of conventional rehabilitation therapy and the increasing demand for gait rehabilitation. Clinical considerations are often taken for granted amongst other design considerations. This paper attempts a review of the clinical considerations as well as reporting preliminary findings on the development of the iMAMS lower extremity rehabilitation exoskeleton.**

***Index Terms*—exoskeleton, gait rehabilitation, clinical, ergonomics, lower extremities**

I. Introduction

According to the World Health Organisation's (WHO) 2013 World Health statistics report, 8% of Malaysia's population is well above 60 years old [1]. The Malaysian Ministry of Health's annual report 2011 reported about 11% and 7.2% of children aged between 0 to 18 years are detected with physical and cerebral palsy disabilities [2]. Gait disorders are not uncommon amongst the aforementioned percentiles and it also affects the range between the age groups [3]. Gait, essentially is the walking pattern of a person. It is the ability of one to maintain balance and assume the upright position as well as the aptitude to initiate and sustain rhythmic stepping [4]. Gait abnormalities may originate from cerebellar disease, neuromuscular disease, definable central nervous degenerative disorder, cognitive impairment, stroke, brain or spinal injury, cardiac disease or other general conditions that may cause this disorder [4]-[6].

The demand for rehabilitation services is growing rapidly due to the rising number of aging society globally as well as other factors that contribute towards the need of such services [1]-[2], [4]-[6]. Studies have shown that a patient's mobility may be improved with continuous locomotor activity [7]-[9]. At present, the therapy which facilitates this activity requires the aid of at least two physical therapists in assisting the patient to move their legs in emulating walking sequence [10]. Nonetheless, this form of therapy is laborious to the therapist as well as cost demanding. Attempts have been made by the research community at large by exploring the engagement of robotics to address the drawbacks of conventional rehabilitation therapy and the increasing demand for gait rehabilitation.

A sharp increase of 47% in articles on rehabilitation robotics submitted to the International Conference on Rehabilitation Robotics (ICORR) from the year 1997 to 2007 echoes the significance of therapeutic robotics [11]. Motivated in facilitating rehabilitation initiatives in Malaysia especially gait rehabilitation, Innovative Manufacturing, Mechatronics and Sports (iMAMS) Laboratory, Universiti Malaysia Pahang is embarking on the development of a lower extremity exoskeleton for the intended purpose. This paper attempts a review of the clinical considerations in the development of rehabilitation exoskeleton as well as reporting preliminary findings of the iMAMS exoskeleton.

II. Exoskeletons: History and Development

Exoskeleton by definition is essentially a hard outer structure that provides protection or support. From an engineering standpoint, specifically mechatronics, exoskeletons are electromechanical wearable devices intended for human use in order to enhance the physical capacity of the human wearer [12]. Exoskeletons in

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general may be categorised into performance-augmenting and rehabilitation robots, in which the former enhances the capabilities of a healthy user whilst the latter is an assistive device for a patient with a motor pathology and is often referred to as active orthoses [13]. Both forms of exoskeletons are very similar in terms of functional level, nonetheless the human interfaces as well as control objectives are different from each other.

Initial works on the conceptual design of exoskeletons has been reported as early as 1890, as the concept was patented by Yagn [14]. This was followed by a research paper issued by the U.S. Army Exterior Ballistics Laboratory in 1963 [15], [16]. The paper dealt with the intended design of a load-carrying augmentation exoskeleton. It addressed significant issues on the development of exoskeletons despite the fact it did not materialise, viz. the locomotion behaviour, human machine interface, power supply, actuators as well as sensing and control. Hitherto, the first known exoskeleton developed is the “Hardiman” (Human Augmentation Research and Development Investigation) circa 1967 by a research collaboration from General Electric Research and Cornell University [14], [15], [17]. The exoskeleton has 30 DOFs (degree of freedom), weighs 680kg and has the load lifting capability of 680kg. Active research on exoskeletons was resuscitated with the development of BLEEX (Berkeley Lower Extremity Exoskeleton) [18], [19].

As mentioned earlier, exoskeletons may be distinguished into either for performance augmentation or rehabilitation purpose. BLEEX which was funded by the U.S. Defense Advanced Research Projects Agency (DARPA) falls under the first category by allowing additional payload to be carried. Other notable DARPA funded exoskeleton research were the Sarcos Research Corporation WEAR (Wearable Energetically Autonomous Robot) [20] and the MIT exoskeleton [21]. Nanyang Technological University also developed their own lower extremity exoskeleton dubbed NTU-LEE [22] which is similar to BLEEX. Hybrid Assistive Limb (HAL-3) was developed by University of Tsukuba with the same intent focusing on lower extremity [23].

Rehabilitation exoskeletons may be further classified into treadmill-based, over-ground and also mobile medical exoskeletons. Lokomat [24], LOPES [25] and ALEX [26] are amongst the treadmill based rehabilitation exoskeletons available. Over-ground rehabilitation exoskeleton has the same function as the former, however facilitates over-ground gait training. Among the notable models are WalkTrainer [27] and NTU’s NaTUre-gaits [28]. Portable mobile medical exoskeleton requires the patient to balance themselves which is in contrast to rehabilitation robots which are often equipped with a body weight support system. eLEGS, REX and ReWalk are examples of such form of exoskeletons [19], [29], [30]. The following section will discuss further on the design requirement in developing a lower extremity exoskeleton.

III. Design Considerations

In the development of lower extremity exoskeletons, the following design considerations must be taken into account [15], [16], [19]. (1) The understanding of human lower limb biomechanics especially the kinematics and functionality of hip, knee and ankle joints. (2) Human machine physical interface as it responses for transmission of mechanical power from the exoskeleton to human, in which improper design may result severe injury, if not insufficient support of the device (3) Human machine interaction which entails the control of the exoskeleton due to the users intention and (4) The design of the power source, actuator and actuation mechanism of the actuation system. Clinical considerations should also be incorporated, as the basis of the development should not only be restricted to scientific concept or technical feasibility only [31].

A general overview on essential biomechanics with regard to gait rehabilitation is apt prior to discussing further on the clinical considerations. Amongst common motions considered in gait rehabilitation are walking as well as raising to standing motions. Walking motions are mainly divided into two basic phases, namely the stance or support phase and the swing phase along the sagittal plane. The Rancho Los Amigos gait analysis committee [32] suggests that within the two basic phases, there are further eight gait phases viz. for the stance phase are the initial contact, loading response, mid-stance, terminal stance and pre-swing phases, whilst for the swing phase include initial swing, mid-swing and terminal swing. Fig. 1 illustrates these phases.

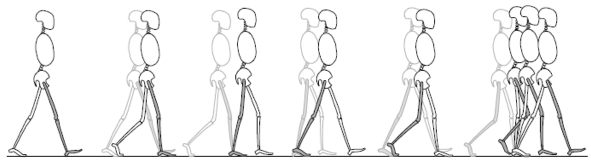

Figure 1. Gait phases along the sagittal plane for normal gait [32]

As gait motions are cyclic in nature, the gait phases are repeated in each stride. A healthy person would exhibit normal gait in which the phases are in sequence from an initial contact phase to the terminal swing phase. However, abnormal gait would differ from those of normal gait, hence the effectiveness of a rehabilitation treatment prior and after the treatment may be analysed and gauged.

Standing up motion is basically the motion of raising to a standing position from a sitting position. This activity may be divided into four phases. The first phase is a flexion-momentum phase, this phase initiates the initial momentum for rising. The second phase commences as the individual leaves the chair seat and ends at maximal ankle dorsiflexion (dorsiflexion is the movement where the angle between the dorsum (superior surface) of the foot and the leg is decreased). This third phase is an extension phase as the body rises to its full upright position. The fourth and the final phase is a stabilization phase. These phases are characterised in terms of momentum and stability [33]. Fig. 2 depicts the aforementioned phases.

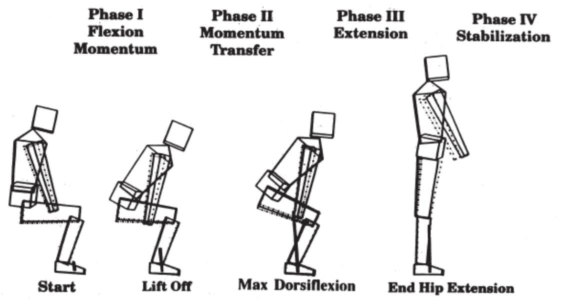

Figure 2. Phases of tanding up motion [33]

The typical biological limb's degree of freedom (DOF), range of motion (ROM) and torque is tabulated in Table I. These guidelines should be adhered in the development of any type of exoskeletons to ensure its robustness to the human wearer. Nonetheless, the minimum recommended DOF for locomotion includes a single DOF at the foot joint to allow extension for the metacapophalangeal joint, a single DOF at the ankle joint to allow flexion and extension, a single DOF at the knee joint to allow flexion motion, three DOF for both hip and pelvis joint to allow flexion and extension, abduction and adduction, medial and lateral rotation along the hip as well as rotations in the coronal, sagittal, and transverse planes for the pelvis joint, respectively [34].

TABLE I. BIOMECHANICAL PROPERTIES OF HUMAN LOWER LIMB(AFTER [19])

Properties	Joints	Biological Limb
Degrees of Freedom	Pelvis	6
	Hip	3
	Knee	2
	Ankle & Foot	4
Range of Motion (°)	Hip	140/15 (a) 40/30-35 (b) 15-30/60 (c)
	Knee	120-140/0-10 (a)
	Ankle & Foot	40-50/20 (a) 30-35/15-20
Torque (Nm)	Hip	140/120 (a)
	Knee	140/15 (a)
	Ankle & Foot	b (a)

(a) Flexion/Extension (b) Adduction/Abduction (c) Internal/External

Previous exoskeleton designs provide little information on the effectiveness in reducing the metabolic rate of walking and energy expenditure. D. P. Ferris *et al.* [35] suggests that one of the important results that need to be measured is neural mechanisms as well as the rate of metabolic energy cost that is involved. Neural mechanisms may be measured by means of electromyography (EMG) to evaluate changes in muscle activation timing and amplitude during lower limb exoskeleton use in evaluating the changes in muscle activation timing and amplitude. The second criterion that ought to be measured is the change in metabolic energy cost whilst donning the exoskeleton. This energy cost may be computed by considering the consumption of O_2 and the production CO_2.

A unified vision must be taken from both engineers as well as clinicians in order to address the shortcomings on existing exoskeletons and to further propel the future of rehabilitation robots. In light of our discussion, Hidler and S. Lum raised three interesting fundamental questions [36] which were further argued by Low [19], namely the goal of rehabilitation robots, the barrier for rehabilitation robots to receive clinical acceptance and also on how robot-assisted rehabilitation would look like in the future. The ensuing subsections will delve into these questions further.

A. Goal of Rehabilitation Robots

The ultimate goal of rehabilitation robots is to facilitate its stakeholders' viz. patients as well as the therapist in the overall therapy course. Rehabilitation robots are often thought to assist rehabilitative activities which are deemed difficult, laborious, or impossible for the therapist to manage unaided. Conventional over-ground gait training for instance, requires a minimum of two or three therapists to assist the patient to walk. If necessary, parallel bars are used to ensure the patient's safety. All of the patient's weight is placed on the floor whilst the upper limbs are used as supports on the parallel bars in the event of such usage of parallel bars are necessary along with the assistance of therapists. Often, therapists experience fatigue due to unergonomic posture imposed by them throughout the sessions. In situations where parallel bars are not employed, these sessions may inflict further injuries to the patient, if the average therapists are unable to sustain the weight of the patient due to exhaustion. Such undesirable incidents will hamper rehabilitation initiatives as patients may refuse subsequent training sessions. These tasks, which are initially thought and found to be difficult by therapists, are now possible owing to the presence of robotics. Assistive tools such as the ZeroG [37] illustrated in Fig. 3 is capable in relieving a share of the patient's body weight to compensate the weakness of the lower limbs which in turn may safeguard the patient from falling. Therefore, principally any development of rehabilitation robots should be driven by catering the needs whilst ensuring the safety of the aforementioned stakeholders.

Figure 3. The ZeroG assistive robot [37].

B. Clinical Acceptance

In order to achieve the aforementioned goals as well as to foster clinical acceptance, the inclusion of clinicians during the planning stage which is undeniably the most crucial stage of the development cycle of any product, is vital. Their knowledge and critical feedbacks has to be considered by engineers, as this fruitful exchange allows the end users (which are essentially clinicians) to have a sense of ownership as well as facilitate towards the successful development of such rehabilitation devices. Often, these rehabilitation devices are perceived to interrupt well-established therapeutic procedures. Hence, rehabilitation robots should act as intervention tools to assist them where it is not possible for them to do it on their own instead otherwise. These devices should be able to adapt with a wide spectrum of the patient's anthropomorphic physique and capabilities as well as providing feedback modalities during therapy sessions for documentation process. This enables the clinicians to monitor the progress made by the patient throughout the rehabilitation process. To ensure that rehabilitation robots are accepted and deployed by the clinical community, these devices should not be difficult or cumbersome to be employed. Such devices would not likely be adopted if it is too time consuming to set-up as the limited time therapists has per session. If therapy sessions could begin quickly, this would in turn translate into significant outcomes as the patient would have the luxury of more therapeutic activities. In essence, as rehabilitative robots requires a lot of interactions between human and the device, the practicality of its usage should not be compromised.

C. The Future of Robotic Rehabilitation

The clinical community opines that the rehabilitation process for a neurological injury episode or anything akin to it should be an extended or a lifelong process and not only restricted within the several months after injury. Nonetheless, if such model is adopted in Malaysia, the cost associated with it along with limited facilities available at government funded hospitals at present makes it rather impossible for patients to get such sessions daily. Robotic assistive devices may provide a solution for this predicament in the near future, as telemedicine and telerehabilitation are receiving due attention among the research community [38]. Owing to such innovative methods, the focus has also shift towards home-based rehabilitation. Therefore, it is not unimaginable that one day, therapists and doctors could work with patients at home via remote monitoring. This would enable patients to carry on with their rehabilitation sessions beyond the present healthcare system allows.

IV. Discussion

Over the past decade, it is apparent that active research has been conducted on both performance augmentation as well as rehabilitation exoskeletons. The fusion of knowledge obtained from both forms of exoskeletons has brought into inception innovative over-ground and other types of rehabilitation robots. In the near future, we will perhaps be introduced to mobile assistive devices that would make home-based rehabilitation possible. Nonetheless, in order to produce and fabricate clinically accepted devices, a unified view must be taken from both engineers and the clinical community. Only once this is harmonised, are we able to see more adoption of rehabilitation robots in hospitals that is beneficial towards the society rather than pure academic outcomes. Hitherto, several rehabilitation robots have already gone through clinical trials, such as eLEGS, ReWalk and NaTUre-gaits [19], [29], [30].

Design considerations such as the understanding of human lower limb biomechanics, human machine physical interface, human machine interaction, and power source design and actuation system are essential in the development of an exoskeleton. Clinical considerations in the design phase of rehabilitation robots are also vital as advances in this field are driven by it. The development of iMAMS lower extremity exoskeleton is underway and will follow suit this particular design consideration which is often dismissed.

Gait analysis was performed on a healthy male subject with the following physical parameters; Height (166cm), Weight (63kg), joint center to center length of thigh (0.36m), lower leg (0.42m) and feet to ground (0.16m). A digital single lens reflex camera is used to capture a video of the subject walking at 60fps. Reflective markers were placed on the subject's joints. A motion analysis software Kinovea® was used to compute the required angular displacements. Fig. 4 illustrates how the software detects the markers in the motion analysis.

Figure 4. Motion analysis using Kinovea®

The angle of flexion/extension is taken from the ordinate axis passing through the joint which is parallel to the sagittal plane. The angular displacement profile obtained from the experimentation for two gait cycles for a slow paced walking is illustrated in Fig. 5. In this preliminary study, the range of motion obtained are as follows; Hip (-10.5°–13.2°), Knee (4°–62°) and Ankle (-13.4°–10.8°). The results obtained are in good agreement with [19]. Further investigation is currently underway in refining these results. Data from the gait analysis will be used to define the range of motion and also be used as basis for control strategies in the development of the exoskeleton.

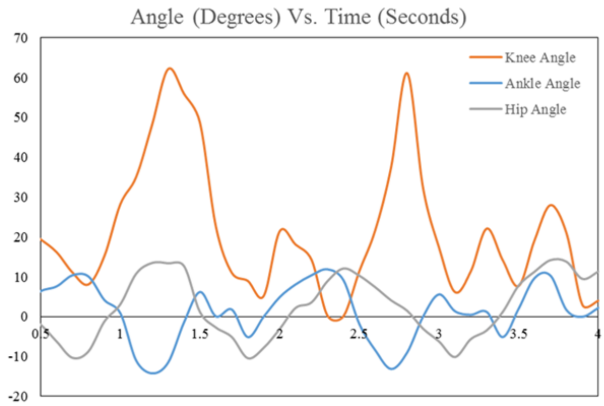

Figure 5. Angular displacement profile.

Fig. 6 depicts a prototype (Mark I) of the exoskeleton which consists of a linear actuator which actuates the knee as well as a DC motor actuating the ankle. The further development of the exoskeleton will address issues such as the practicality of the design to ensure minimum set-up time, minimum therapist intervention whilst assisting the patient to walk, ergonomic considerations for both patients as well as therapists and providing precise natural gait motion therapy to the patients.

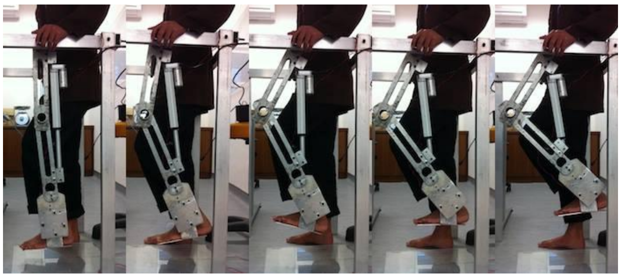

Figure 6. Mark I of iMAMS lower extremity exoskeleton.

V. Conclusion

This paper highlights clinical considerations that ought to be weighed in the development of rehabilitation exoskeletons as well as preliminary results on the development of iMAMS exoskeleton. Such devices should be designed to assist therapist to perform tasks, which are deemed difficult or even inconceivable for the therapist to perform on their own whilst providing the best rehabilitation therapy to patients under the advice of clinicians along with practical designs. Further investigations on the development of the iMAMS lower extremity exoskeleton will be reported imminently.

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References

[1] World Health Organization, World health statistics 2013, World Health Organization, 2013.

[2] Ministry of Health, Annual Report 2011, Malaysian Ministry of Health, 2011.

[3] L. Sudarsky and M. Ronthal, “Gait disorders among elderly patients: A survey study of 50 patients,” *Arch.Neurol.*, vol. 40, no. 12, pp. 740-743, 1983.

[4] J. Nutt, C. Marsden, and P. Thompson, “Human walking and higher‐level gait disorders, particularly in the elderly,” *Neurology*, vol. 43, no. 2, pp. 268-268, 1993.

[5] O. Franch, L. Calandre, J. Álvarez-Linera, E. D. Louis, F. Bermejo-Pareja, and J. Benito-León, “Gait disorders of unknown cause in the elderly: Clinical and MRI findings,” *J. Neurol. Sci.*, vol. 280, no. 1, pp. 84-86, 2009.

[6] S. Murray and M. Goldfarb, “Towards the use of a lower limb exoskeleton for locomotion assistance in individuals with neuromuscular locomotor deficits,” in *Proc. IEEE Annual International Conference on Engineering in Medicine and Biology Society*, 2012, pp. 1912-1915.

[7] World Health Organization, World Health Statistics 2011, World Health Organization, 2011.

[8] V. Dietz and S. J. Harkema, “Locomotor activity in spinal cord-injured persons,” *J. Appl. Physiol*, vol. 96, no. 5, pp. 1954-1960, 2004.

[9] A. Wernig, S. Müller, A. Nanassy, and E. Cagol, “Laufband therapy based on ‘rules of spinal locomotion’is effective in spinal cord injured persons,” *Eur. J. Neuro Sci.*, vol. 7, no. 4, pp. 823-829, 1995.

[10] D. Ferris, K. Gordon, J. Beres-Jones, and S. Harkema, “Muscle activation during unilateral stepping occurs in the nonstepping limb of humans with clinically complete spinal cord injury,” *Spinal Cord*, vol. 42, no. 1, pp. 14-23, 2004.

[11] J. B. Bae, “Mechatronic considerations of assistive systems for gait rehabilitation,” Diss. University of California, Berkeley, 2011.

[12] H. Krebs, L. Dipietro, S. Levy-Tzedek, S. Fasoli, A. Rykman-Berland, *et al.*, “A paradigm shift for rehabilitation robotics,” *Engineering in Medicine and Biology Magazine, IEEE*, vol. 27, no. 4, pp. 61-70, 2008.

[13] A. Gams, T. Petric, T. Debevec, and J. Babic, “Effects of robotic knee-exoskeleton on human energy expenditure,” *IEEE Transactions on Biomedical Engineering*, vol. 60, no. 6, pp. 1636-1644, 2013.

[14] R. Jimenez-Fabian and O. Verlinden, “Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons,” *Med. Eng. Phys.*, vol. 34, no. 4, pp. 397-408, 2012.

[15] X. Zhang, Q. Guo, C. Zhao, Y. Zhang, and X. Luo, “Development of a lower extremity exoskeleton suit actuated by hydraulic,” in *Proc. International Conference on Mechatronics and Automation*, 2012, pp. 587-591.

[16] Y. W. Hong, Y. King, W. Yeo, C. Ting, Y. Chuah, J. Lee, and E. Chok, “Lower extremity exoskeleton: Review and challenges surrounding the technology and its role in rehabilitation of lower limbs,” *Australian Journal of Basic and Applied Sciences*, vol. 7, no. 7, pp. 520-524, 2013.

[17] A. M. Dollar and H. Herr, “Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art,” *IEEE Transactions on Robotics*, vol. 24, no. 1, pp. 144-158, 2008.

[18] B. R. Fick and J. B. Makinson, *Hardiman I Prototype for Machine Augmentation of Human Strength and Endurance: Final Report*, Schenectady, NY: General Electric Company, GE Tech. Rep. S-71-1056, 1971.

[19] A. B. Zoss, H. Kazerooni, and A. Chu, “Biomechanical design of the berkeley lower extremity exoskeleton (BLEEX),” *IEEE/ASME Transactions on Mechatronics*, vol. 11, no. 2, pp. 128-138, 2006.

[20] K. Low, “Robot-assisted gait rehabilitation: From exoskeletons to gait systems,” in *Proc. Defense Science Research Conference and Expo*, 2011, pp. 1-10.

[21] E. Guizzo and H. Goldstein, “The rise of the body bots [robotic exoskeletons],” *Spectrum, IEEE*, vol. 42, no. 10, pp. 50-56, 2005.

[22] C. J. Walsh, K. Pasch, and H. Herr, “An autonomous, underactuated exoskeleton for load-carrying augmentation,” in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2006, pp. 1410-1415.

[23] X. Liu and K. Low, “Development and preliminary study of the NTU lower extremity exoskeleton,” in *Proc. IEEE Conference on Cybernetics and Intelligent Systems*, 2004, pp. 1243-1247.

[24] H. Kawamoto and Y. Sankai, "Comfortable power assist control method for walking aid by HAL-3," in *Proc. IEEE International Conference on Systems, Man and Cybernetics*, 2002, vol. 4, pp. 6.
[25] M. Frey, G. Colombo, M. Vaglio, R. Bucher, M. Jorg, and R. Riener, "A novel mechatronic body weight support system," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 14, no. 3, pp. 311-321, 2006.
[26] D. P. Ferris, G. S. Sawicki, and A. R. Domingo, "Powered lower limb orthoses for gait rehabilitation," *Topics in Spinal Cord Injury Rehabilitation*, vol. 11, no. 2, pp. 34, 2005.
[27] S. K. Banala, S. K. Agrawal, A. Fattah, V. Krishnamoorthy, W. Hsu, J. Scholz, and K. Rudolph, "Gravity-balancing leg orthosis and its performance evaluation," *IEEE Transactions on Robotics*, vol. 22, no. 6, pp. 1228-1239, 2006.
[28] M. Bouri, Y. Stauffer, C. Schmitt, Y. Allemand, S. Gnemmi, R. Clavel, *et al.*, "The WalkTrainer: A robotic system for walking rehabilitation," in *Proc. ROBIO'06. IEEE International Conference on Robotics and Biomimetics*, 2006, pp. 1616-1621.
[29] P. Wang, K. Low, A. Tow, and P. Lim, "Initial system evaluation of an overground rehabilitation gait training robot (NaTUre-gaits)," *Adv. Rob.*, vol. 25, no. 15, pp. 1927-1948, 2011.
[30] T. Swift, K. Strausser, A. Zoss, and H. Kazerooni, "Control and experimental results for post stroke gait rehabilitation with a prototype mobile medical exoskeleton," in *Proc. ASME 2010 Dynamic Systems and Control Conference*, 2010.
[31] M. Wirz and R. Rupp, "Clinical application of a robotic device for locomotion," in *Converging Clinical and Engineering Research on Neurorehabilitation*, Berlin Heidelberg: Springer, 2013, pp. 973-975.
[32] J. Perry, "Gait analysis: Normal and pathological function," SLACK, 1992.
[33] M. Schenkman, R. A. Berger, P. O. Riley, R. W. Mann, and W. A. Hodge, "Whole-body movements during rising to standing from sitting," *Phys Ther.*, vol. 70, no. 10, pp. 638-651, 1990.
[34] H. P. Crowell, III, "Human engineering design guidelines for a powered, full body exoskeleton," U.S. Army Res Lab, Aberdeen Proving Ground, MD ARL-TN-60, Jul. 1995.
[35] F. P. Daniel, S. S Gregory, and D. A. Monica, "A physiologist's perspective on robotic exoskeletons for human locomotion," *Disability & Rehabilitation*, vol. 4, no. 3, pp. 507-528, 2007.
[36] J. Hidler and P. S. Lum, "The road ahead for rehabilitation robotics," *Journal of Rehabilitation Research and Development*, vol. 48, 2011.
[37] T. Nef, "ZeroG: Overground gait and balance training system," 2011.
[38] D. Kairy, P. Lehoux, C. Vincent, and M. Visintin, "A systematic review of clinical outcomes, clinical process, healthcare utilization and costs associated with telerehabilitation," *Disability & Rehabilitation*, vol. 31, no. 6, pp. 427-447, 2009.

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