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A Survey in the Different Designs and Control Systems of Powered Exoskeleton for Lower Extremities

Renann G. Baldovino*, Rodrigo S. Jamisola, Jr.**
De La Salle University, Manila, Philippine, renann.baldovino@dlsu.edu.ph
*** Botswana International University of Science and Technology, Palapye, Botswana, jamisolajr@biust.ac.bw*

Review Article

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Abstract

In this paper, previous studies in powered exoskeleton and their contributions in the field of robotics technology are presented, together with their corresponding control system. Specific problems and issues that were encountered and the solutions made to resolve the problems will be discussed. Gait cycle analysis and human body dynamic model will also be covered in the study to understand the biomechanics and the dynamics behind human walking.

Keywords: biofeedback; exoskeleton; lower extremitie; gait analysis

1. Introduction

In the late 1960s, two countries, US and Yugoslavia, started the human exoskeleton research. US focused primarily on making exoskeletons for strength amplification, while Yugoslavia on rehabilitation [1, 2]. By definition, exoskeletons are wearable devices placed around the human body. There are other studies that focus only on some parts of the body just like the arms and the legs or the lower extremities. Lower extremity exoskeletons can be used for different purposes: performance amplification, locomotion or ambulatory, and rehabilitation [3]. Performance amplification is used to increase the user's strength and endurance. This type of exoskeleton is widely used in military. While in the other hand, exoskeletons designed for ambulatory and rehabilitation are used to assist patients who have walking disabilities.

2. Survey of Exoskeleton Research Works

2.1. Yugoslavian exoskeleton

Research activities on powered-exoskeleton began on the work of M. Vukobratovic [4] of Mihailo Pupin Institute, Yugoslavia, see Fig 1a. Their research objective is to develop an exoskeletal device that can aid people in walking. Pneumatic actuators were used on their first version utilizing four degrees of freedom in the hip joint, knee joint and both legs. The robotic leg was externally powered by a predetermined periodic motion in order to compromise the heavy weight and large size of the air supply for the actuators. Another problem of the device was the issue on maintaining proper balance. A disable patient could not walk alone using the device without the assist of another person. In 1971, the work was extended to allow incorporation of overall stability control by adding a torso frame. With the use of controllers, the limbs make it easy to move along the designed path and with the zero moment point (ZMP), the overall dynamic stability became more stable [5].

***Corresponding Author : Rodrigo S. Jamisola, Jr.*
Email Address: jamisolajr@biust.ac.bw

To provide patient feedback, pressure sensors were equipped at the exoskeleton soles to improve stability and wearer's safety. Foot sensors were developed to analyze pressure on the foot during gait cycle analysis. The problem associated using this sensor, especially rubber transducers, is that they will wear out over time [6].

2.2. GE Hardiman

Almost in the same year when Yugoslavia started the development of exoskeletons, General Electric Research, in collaboration with Cornell University and the US Office of Naval Research Institute, developed a full-body powered exoskeleton prototype that they named as Hardiman, see Fig 1b. This hydraulically-powered robot, having 30-DOFs, was impractical due to its 680 kg. weight. Its objective is to amplify 25 times the strength of its wearer. Unfortunately, the project turned out not to be successful because it was too large and bulky. Though they failed to implement the prototype; it was able to address solutions in technological issues like power supply and human-machine interface [7-10].

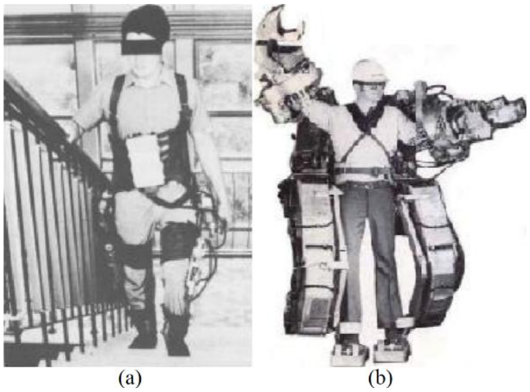

Fig.1 (a) Exoskeleton Walking Aid[4]; (b) GE's Hardiman[7]

2.3. Pitman

Jeffrey Moore, an engineer of Los Alamos National Laboratory, proposed his project Pitman [11]. The project is designed and intended for US soldiers. In his paper, a network of brain-scanning sensors were incorporated in the helmet. Problem with his research is that he never tried to address some issues on building the exoskeleton such as power supply.After the Hardiman and Pitman project, M. Rosheim expanded the idea of these two in one in his paper by incorporating singularity-free pitch–yaw type joints. He presented a full-body exoskeleton concept consisting of 26-DOF joints[12].

2.4. BLEEX

The US Defense Department funded an exoskeleton project that will be used by soldiers, firefighters and relief workers to carry major loads like food supply, rescue equipment, first-aids and weaponry having minimal effort over long distances and extended time periods. The name of the project was BLEEX, short for Berkeley Lower Extremity Exoskeleton, see Fig 2. The idea came from Prof. Kazerooni of the University of California Berkeley's Human Engineering and Robotics Laboratory [13].

The primary objective of BLEEX is to design an autonomous exoskeleton for human strength augmentation and enhancement[14]. It also addressed and solved problems in ergonomics, maneuverability, robustness, weight factor and durability of early lower-limb exoskeletons [15]. There are two BLEEX versions. The first one is composed of two powered-anthropomorphic legs, a power unit and a backpack-like frame. In order to address problems in power supply, BLEEX uses a state-of-the-art small hybrid power source capable of delivering a large hydraulic locomotion power.

Aside from power supply performance, BLEEX also addressed issues in robustness and reliability by designing a system capable under extreme operating conditions and environment. After a series of experimentation, the researchers were able to conclude and identify problems in mobility requirements like payload specifications, terrain and speed parameters [16, 17].

BLEEX leg has three degrees-of-freedom (dof) at the hip, one dof at the knee, and three dof at the ankle. Force sensors were also attached under the soles of both feet. It uses a hybrid control to add robustness whenever there is a change in the backpack payload. Position control and sensitivity amplification control is employed to the swing leg for smooth transitions as the wearer walks. Moreover, position controls were also employed to require the pilot to wear seven inclinometers to measure human limb and torso angles [18].

Fig.2 BLEEX[13] (image credit to Prof H. Kazerooni)

2.5. Sarcos exoskeleton

Another US Defense funded-exoskeleton project is the Sarcos Exoskeleton project. This was started and developed first by the Sarcos Research Corporation in Salt, Lake City, University of Utah before the project was transfer to Raytheon in 2007. They started to develop exoskeletons for the US Army in 2008. Sarcos was designed not only to increases the strength of the wearer but also its endurance because of the engine that is used to run servo motors [19, 20]. In 2008, Sarcos had become popular and well-known in developing efficient hydraulically-actuated exoskeleton [21, 22].

2.6. Hybrid-assistive leg (HAL)

A group of researchers in the University of Tsukuba, in cooperation with the Cyberdyne Systems Company, developed an exoskeleton concept to address both performance augmentation and rehabilitative purposes. They dubbed the exoskeleton Hybrid-Assistive Leg (HAL) [23], which is a full-body battery-powered suit designed to support the elderly and gait-disordered people. HAL is mainly used by disabled patients in hospitals to assist them in moving from one bed to another, and can also be modified so that patients can use it for rehabilitation, see Fig 3a.

Currently, there are two HAL protoypes, HAL-3 and HAL-5. The first prototype has bulkier servo-motors and only has the lower limb function. It is consist of a system with four actuated joints at the hip and knee of both legs, with passive joints at the ankles. Compared from the early development, the latest prototype HAL-5 is composed of a full-body exoskeleton for arms, legs, and torso. The exoskeleton is currently capable of allowing the u to lift and carry about five times as much weight as he could lift and carry unaided. The leg structure of HAL-5 powers the flexion and extension joints at the hip and knee using a DC motor. The main challenge is to detect the user's motion intention. To accomplish this, nerve signals that flow along muscle fibers should be measured which are generally sensed with electromyograms. Then, a control unit determines the required assistive power and commands the actuators to produce a specific torque [24]. HAL performance was further improved when the exoskeleton is modelled through an inverted pendulum with gravity, inertia and viscous friction. A compensation term is added to the supporting torque to regulate the joint impedance [25-27]. In a separate research by Lee [28], another consideration was made for the operator's leg to act as a pendulum model. From this model, it can easily identify the physical parameters around human's knee joints and leg movement. Using myoelectricity, the effectiveness of adjusting the natural frequency in power assist control can be tested.

2.7. Nurse-assisting robot

The Nurse-assisting exoskeleton [29], a full-bodied exoskeleton project in Kanagawa Institute of Technology, helps in assisting nursing personnel when handling patients especially during patient transfer, see Fig 3b. The robotic suit covers shoulders, arms, torso, waist the lower limbs, weighing a total of 30 kg. The lower limb components include direct-drive pneumatic rotary actuators for the flexion and extension of the hips and knees. Air pressure is supplied from small air pumps mounted directly to each actuator, allowing the suit to be fully portable [30, 31].

2.8. LOPES

Lower-extremity powered exoskeleton or LOPES [32] is an assistive-type of exoskeleton published by Ekkelenkamp et al. in 2005. Its main objective is to implement a gait rehabilitation robot on treadmills for stroke patients. LOPES can perform in two different modes: 'patient-in-charge' and 'robot-in-charge' mode. The first mode works when the patient tries to walk freely without the robot's action while the second mode is just the opposite of the first mode wherein the robot is the one controlling the patient especially if the user is not capable to perform [33-36].

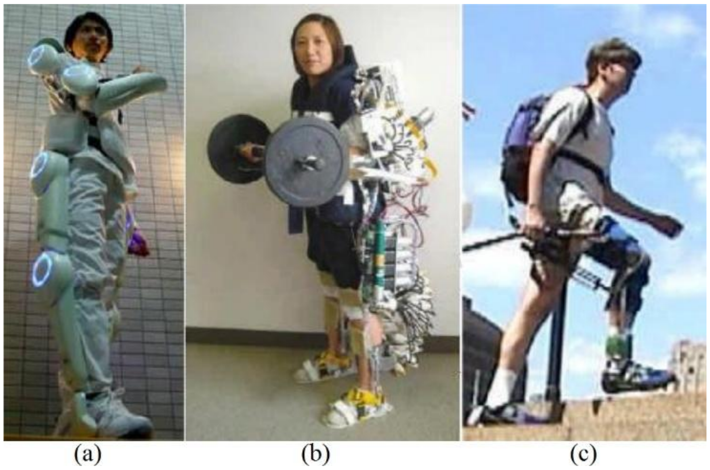

Fig.3(a) HAL-525; (b) Nurse-Assisting Exoskeleton[29]; (c) RoboKnee[39] (Creative Commons Attribution)

2.9. NTU exoskeleton

Another wearable lower extremity exoskeleton that was developed in Singapore is the NTU Exoskeleton, see Fig 5a. Its objective is to enhance the human ability in carrying heavy loads with their goal to design and control a power assist system that integrates a human's intellect as the control system for feedback and sensory purposes. The exoskeleton system is composed of two systems: the inner and outer exoskeleton. The inner exoskeleton is responsible for measuring the movements of the wearer and for providing a feedback of these measurements to the outer exoskeleton. On the other hand, the outer exoskeleton is designed to support the whole robotic system especially when the wearer starts to walk.

For the controls, the trajectory of the wearer's foot will be followed with its own footplate during the swing phase of each leg. With this condition, this allows the wearer to provide the necessary information like the desired velocity and gait length. The NTU Exoskeleton follows the concept of ZMP in maintaining its balance during motion. The controller moves the actuators in such a way that the ZMP remains within the support region, which is the footprint. The ground reaction forces are also measured using force pressure sensors attached in the exoskeleton feet [37, 38].

2.10. RoboKnee

RoboKnee [39] is a simple exoskeleton,having one *dof*, developed by Collins of the University of Michigan, see Fig 3c. The robot is designed to assist its wearer in climbing stairs and performing deep knee bends. The device is consists of a linear series elastic actuator (SEA) connected to the upper and lower portions of a knee brace, see Fig 4. Its design is very straightforward since it only uses one *dof*. An elastic actuator is connected between the upper and lower portions of the knee brace. In order to achieve low impedance and high force with fidelity, SEA was used.

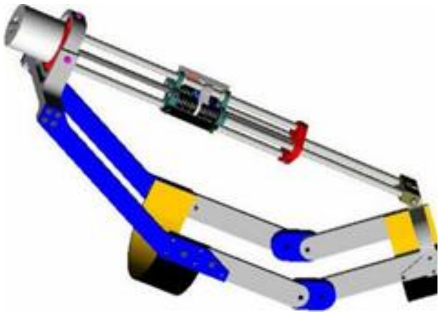

Fig.4RoboKnee SEA design[39]

2.12. ReWalk

ReWalk [40] was the first commercially available walking exoskeleton robot by Argo Medical Technologies. It consists of a light wearable brace support suit that integrates actuators, motion sensors, and a computer-based system powered by rechargeable batteries. In terms of control, the user is actively involved of the person's mobility functions.

2.13. MoonWalker

Another lower limb exoskeleton that was developed in 2009 was the MoonWalker [41]. The main objective of the exoskeleton is for patient's rehabilitation, see Fig 5b. Helping people having weak legs and those suffering from a broken leg to walk. The device can also assist people carrying heavy loads. In order to sustain bodyweight, the exoskeleton uses a passive force balancer. It also uses an actuator to shift the force that is needed for the legs to do an action. The motor is also capable of providing energy in climbing stairs and walking in slopes.

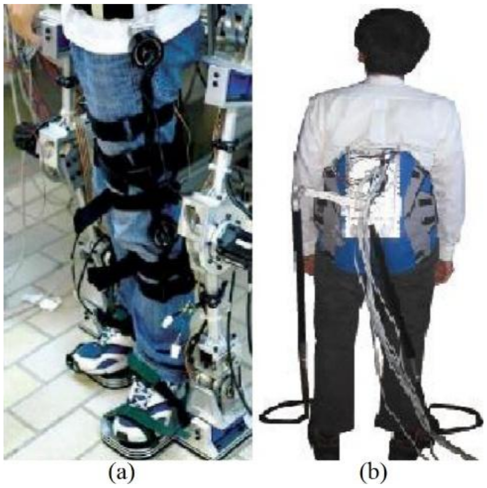

Fig.5(a) NTU Exoskeleton[37]; (b) MoonWalker[41]

3. Biomechanics of Human Walking

Walking and running are the biological basis of all locomotion [42]. These two are the easiest form of locomotion that a human body can perform. In designing an exoskeleton for lower limb, understanding the biomechanical model of human walking is very important. It purely involved mathematics in examining the forces produced by each foot contacting the ground or the ground reaction forces (GRF).

3.1. Ground reaction force (GRF)

In order to measure GRF, a force plate is used. This plate follows the principle of Newton's 3rdlaw of motion. It means that for every one step on the ground, a force vector is produced that is generally downward and backward [43, 44].

3.2. Metabolic cost

In order to determine the effective performance of a powered exoskeleton, getting the metabolic cost of walking is one way to measure it. Metabolic cost is a measure of the increased energy metabolism that is required to achieve a function. Measuring the oxygen consumption rates and carbon dioxide production are ways to determine metabolic cost. This parameter is a good determinant and very useful in comparing the task performance of using and not using an exoskeleton in terms of energetic advantage [45, 46].

3.3. Five goals in walking

Actually, there are five primary goals in understanding walking biomechanics [47]. The first goal is the move the body forward to the desired location with the desired speed. The second goal of walking is to use the minimum amount of energy to move in to that desired location. In order to do this, the body must move in a linear path in accordance to the forward movement. It was proven that the most energy efficient movement is one in which the body moves up and down very little. The third goal of walking is applicable to those people who have painful foot conditions. Ensuring the least amount of pain and putting less pressure on foot during walking to limit discomfort are covered within this goal. The next goal is for the foot to act as a shock absorber when it touches the ground, dispersing the amount of body force as it lands. The last goal is also for the foot to provide a way to propel the body forward after the end of the gait cycle.

3.4. Gait cycle analysis

The gait cycle is used to describe the walking biomechanics, see Fig 6. It was stated earlier that the gait cycle determines the motion of the heel on the ground from initial displacement to the same heel when it contacts to the ground for a second time. In order to clearly understand the human mechanics behind this, the gait cycle is divided into two phases: stance phase and swing phase [48].The stance phase is defined as the interval in which the foot is on the ground. This covers up to 60% of one gait cycle. While the swing phase in the other hand is defined as the interval in which the foot is not in contact with the ground. This is when one foot is on the ground and one in the air. From the evaluation of the gait cycle made by physical therapists, the stance phase was still subdivided into five stages. The five stages are the heel strike, early flat foot, late flat foot, heel rise, and toe-off.

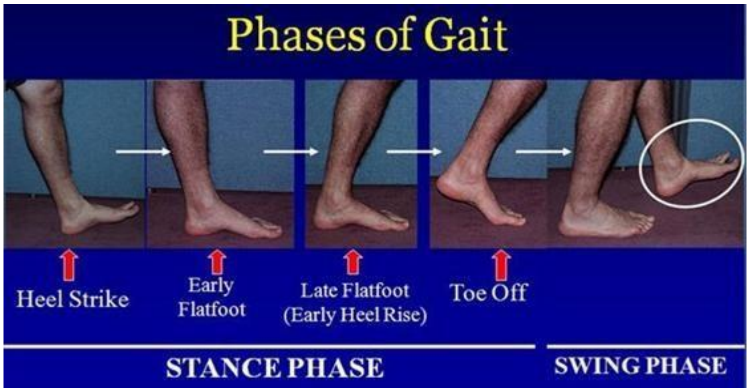

***Fig.6 Gait cycle*[48]**

Swing phase was also divided into two stages: the acceleration to midswing and the midswing to deceleration. The heel strike phase starts when the heel touches the ground first and lasts until the whole foot is on the ground. Early flat foot stage is defined as the moment that the whole foot is on the ground. The phase is said to be in the late flat foot when the heel lifts off the ground. The heel rise phase begins when the heel begins to leave the ground after from being lift. The toe off stage begins as the toes leave the ground. This stage also represents the start of the swing phase.

There are two joints that move during walking: ankle and transverse tarsal joint, see Fig 7. In human anatomy, the ankle joint is formed between the foot and the leg. This joint is responsible for the foot to move up and down. On the other hand, the transverse tarsal joint allows the foot to have some side to side motion [49, 50].

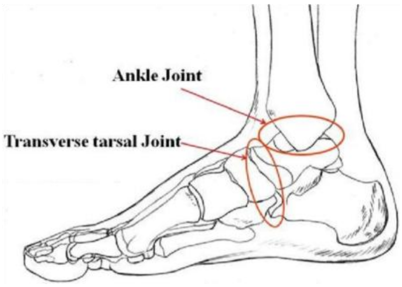

***Fig.7 Joints that move during walking* [49]**

3.4. Human-body dynamic model

Estimating the anthropometric measurements of the human body dynamic model is a reasonable way in determining parameters of mass, location of center of mass and moments of inertia or radii of gyration [51]. There had been previous works related to the computation of these anthropometric parameters that uses geometric modeling, see Table 1. But nowadays, recent technologies in the medical field has allowed researchers to measure the parameters through gamma mass scanners, tomography and magnetic resonance imaging (MRI). Zatsiorsky et al.[52] determined by means of a gamma-ray scanning technique, the relative body segment masses, center of mass positions, and radii of gyration for samples of college-aged Caucasian males and females. From his model, the computed height of the human body is 1.70 m and the estimated weight is 63 kg.

Table 1Anthropometric body parameters[51]

Segment	Mass *(kg)*	Longitudinal length *(m)*	Center of Mass *(m)*	Radii of gyration *(m)*			Moments of inertia(kgm^2)		
				r_s	r_t	r_l	I_{xx}	I_{yy}	I_{zz}
Skull	4.208	0.2050	0.1847	0.0677	0.0736	0.0652	0.0193	0.0228	0.0179
Torso	26.819	0.5325	0.3115	0.1901	0.1805	0.0911	0.9692	0.8739	0.2224
Thorax	18.963	0.3525	0.2212	0.1440	0.1272	0.0956	0.3933	0.3067	0.1734
Pelvis	7.856	0.1800	0.0886	0.0779	0.0724	0.0799	0.0477	0.0411	0.0502
Thigh	9.311	0.3616	0.1304	0.1334	0.1316	0.0586	0.1658	0.1613	0.0320
Shank	3.030	0.4337	0.1915	0.1175	0.1158	0.0403	0.0419	0.0406	0.0049
Foot	0.813	0.2524	0.0989	0.0755	0.0704	0.0351	0.0046	0.0040	0.0010
Upper Arm	1.607	0.2649	0.1496	0.0736	0.0689	0.0392	0.0087	0.0076	0.0025
Forearm	0.869	0.2556	0.1163	0.0667	0.0657	0.0240	0.0039	0.0038	0.0005
Hand	0.353	0.1780	0.0765	0.0945	0.0808	0.0596	0.0032	0.0023	0.0013

4. Control System Design

4.1. Zero moment point (ZMP)

ZMP is a concept related with dynamics and control of legged locomotion [5]. It specifies the point with respect to which dynamic reaction force at the foot contact with the ground does not produce any moment. In short, this is the point where total inertia force equals to zero, with the assumption that the contact area is planar and has high friction avoiding the feet from sliding. There was a preliminary design in 2004 that demonstrated a control principle for lower extremity exoskeleton utilizing ZMP. The research objective focused on the exoskeleton foot design. Using measured human ZMP for reference, the robot's ZMP was modified to achieve ground stability by the application of torso control and GRF [51].

4.2. EMG-based control

Electromyography (EMG) based control is a type of control that uses the skin surface electrodes to be used as input information [53]. EMG is a method use to evaluate and record the electrical activity produced by skeletal muscles [54]. An electromyograph is used to record and visualize the output. When cells are electrically or neurologically activated, this device detects the potential generated by the muscles. There have been many applications associated with the use of EMG especially in the clinical and biomedical field [55-57]. For some powered-exoskeleton designs just like in HAL-5[23], EMG signals act as a control signal from the user's muscle to provide feedback and to initiate leg movement.

A study before in exoskeleton motion assist showcased the use of EMG in order to generate flexible and smooth motions [57, 58]. In 2009, the University of Michigan Human Neuromechanics Laboratory built a pneumatically-powered lower limb exoskeleton that uses a proportional myoelectric control [59]. In this type of control, the wearer's strength is effectively increase while reducing their metabolic cost when walking.

4.3. Active-impedance control

In 2007, another control system in Figure 8, which produces a virtual modification of the mechanical impedance of the human limbs, was proposed. They named the system as active-impedance control. This control emphasizes more on the exoskeleton dynamics [60]. The goal of the research is to improve the dynamic response of the human legs as opposed to the EMG-based control. The difference between the two is that EMG-based requires much computation and calibration in order to model the musculoskeletal system. Whereas active-impedance control is less dependent on these parameters, making it more effective in dealing inaccurate estimations.

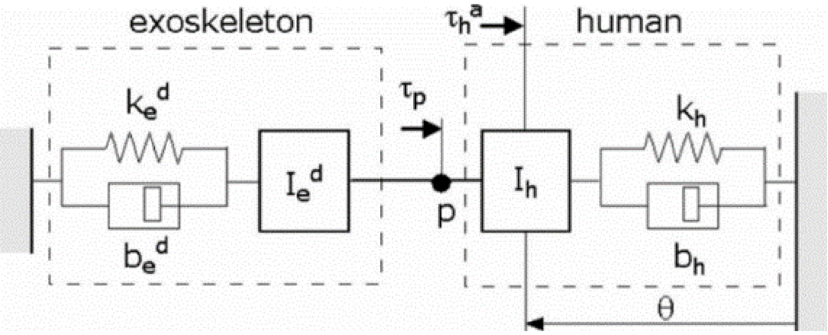

Fig.8 Active-impedance control [60]

4.4. Neural network (NN) control

Previous exoskeleton designs depend much on the use of complex sensors in order to provide feedback between the wearer and robot. Because of the extra weight gained from the sensors, this lead to user discomfort. Neural network (NN) control was introduced to trace the wearer's movement without the use of sensors [61]. Reason behind this is that sensitivity amplification control model relies on the dynamic model and not on the exoskeleton's physical model.

Another type of NN control is the wavelet NN [62]. This adaptive control is used to approximate nonlinear functions as well as complex control mapping. The advantage of this from a normal controller is that the tracking precision is high because of its good advantage in terms of time-frequency localization properties. For adaptive NN control [63], NN and impedance control were both employed. Impedance control was used for the suit control while NN with adaptive learning algorithm was used to compensate the model uncertainty. This will result to a decrease in the power consumption, assisting the wearer to carry out more loads.

4.5. Virtual model control (VMC)

As shown in Figure 9, VMC [64] is a type of motion control framework that uses virtual components in creating virtual forces generated when the virtual components interact with a robot system. Most application of this control is used in bipedal locomotion. With this control algorithm, the biped can walk blindly up and down slopes without sensors.

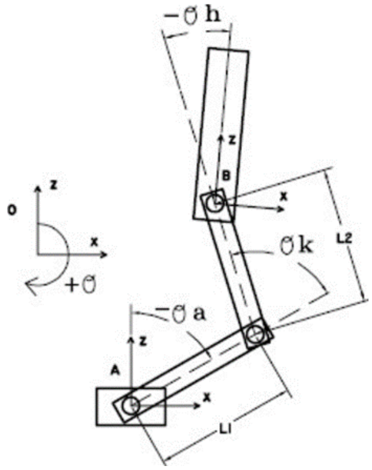

Fig.9 VMC single-leg implementation [65]

For Pratt [65], VMC is a motion control language which uses simulations of virtual components in creating forces, which are applied through joint torques, see Fig 9. VNC design requires the same skills as designing the physical mechanism itself. It can be cascaded with low level VMC to modulate the parameters of the virtual mechanisms.

4.6. Haptics

Haptics is a tactile feedback technology that takes advantage of a user's sense of touch by applying forces, vibrations, and motions. One example of this technology is the haptic exoskeleton based control station or exostation. It is a device that allows the user to wear an exoskeleton-haptic based interface to tele-operate a virtual slave robot[66].

5. Future Design Works and Challenges

Previous studies related to the development of exoskeleton were seen some problems on the hardware design and construction. These include power supply, controls, actuation system, transmissions, and human safety. Reason why designing a very-efficient low-mass exoskeleton is a tough challenge that requires extensive study [67]. Ideally, cooperation between the user and the robot is designed in such a way that the human is the one controlling the robot and not the other way around [68]. In the design, the user should be the one who pilot and control the movements.

Problem in actuator design heavily relies in safety-critical conditions [69]. In meeting safety requirements, several problems will be encountered especially in the concept of safety analysis, engineering design [70] and lifecycle application guidelines. The more actuations you have, more safety conditions you need to consider. Another problem with fully-actuated systems is that they are inefficient and heavy in terms of weight. Designing under-actuated systems that are lighter and only requires small amount of energy will resolve the issue. And lastly, treating the two lower-limb exoskeletons as a single manipulator can be the key towards its holistic coordination and control [71-73].

References

[1] Vukobratović M. Legged locomotion robots and anthropomorphic mechanisms. Mihailo Pupin Institute; 1975

[2] Vukobratovic M, Hristic D, Stojiljkovic Z. Development of active anthropomorphic exoskeletons. Medical and Biological Engineering. 1974 Jan 1;12(1):66-80.

[3] Firmani F, Park EJ. A comprehensive human-body dynamic model towards the development of a powered exoskeleton for paraplegics. Trans. Can. Soc. Mech. Eng. 2009 Jan 1;33(4):745-57.

[4] Vukobratovic M, Borovac B, Surla D, Stokic D. Biped locomotion: dynamics, stability, control and application. Springer Science & Business Media; 1990.

[5] Vukobratović M, Borovac B. Zero-moment point—thirty five years of its life. International Journal of Humanoid Robotics. 2004 Mar;1(01):157-73.

[6] Petrofsky JS, Bweir S. Variable output foot sensors to provide pressure distribution on the foot during gait. Saudi J Rehab. 2002;8:137-42.

[7] Mosher RS. Handyman to hardiman. SAE Technical Paper; 1967 Feb 1.

[8] Gilbert KE. Exoskeleton prototype project: Final report on phase I. General Electric Company, Schenectady, NY, GE Tech. Rep. S-67-1011. 1967.

[9] Gilbert KE, Callan PC. Hardiman I prototype. General Electric Company, Schenectady, NY, GE Tech. Rep. S-68-1081. 1968.

[10] Fick BR, Makinson JB. Hardiman I prototype for machine augmentation of human strength and endurance: Final report. General Electric Company, Schenectady, NY, GE Tech. Rep. S-71-1056. 1971.

[11] Moore JA. Pitman: A powered exoskeleton suit for the infantryman. Los Alamos Nat. Lab., Los Alamos, NM, Tech. Rep. LA-10761-MS. 1986.

[12] Rosheim ME. Man-amplifying exoskeleton. In1989 Symposium on Visual Communications, Image Processing, and Intelligent Robotics Systems 1990 Mar 1 (pp. 402-411). International Society for Optics and Photonics.

[13] Kazerooni H, Steger R. The Berkeley lower extremity exoskeleton. Journal of dynamic systems, measurement, and control. 2006 Mar 1;128(1):14-25.

[14] Zoss AB, Kazerooni H, Chu A. Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). IEEE/ASME Transactions On Mechatronics. 2006 Apr;11(2):128-38.

[15] Chu A, Kazerooni H, Zoss A. On the biomimetic design of the berkeley lower extremity exoskeleton (BLEEX). InProceedings of the 2005 IEEE international conference on robotics and automation 2005 Apr 18 (pp. 4345-4352). IEEE.

[16] Zoss A, Kazerooni H. Design of an electrically actuated lower extremity exoskeleton. Advanced Robotics. 2006 Jan 1;20(9):967-88.

[17] Amundson K, Raade J, Harding N, Kazerooni H. Hybrid hydraulic-electric power unit for field and service robots. In2005 IEEE/RSJ International Conference on Intelligent Robots and Systems 2005 Aug 2 (pp. 3453-3458). IEEE.

[18] Kazerooni H, Steger R, Huang L. Hybrid control of the Berkeley lower extremity exoskeleton (BLEEX). The International Journal of Robotics Research. 2006 May 1;25(5-6):561-73.

[19] Guizzo E, Goldstein H. The rise of the body bots. IEEE SPECTRUM. 2005 Oct;42(10):42.

[20] Huang GT. Wearable robots. Technology Review. 2004 Jul;4.

[21] Dollar AM, Herr H. Lower extremity exoskeletons and active orthoses: challenges and state-of-the-art. IEEE Transactions on robotics. 2008 Feb;24(1):144-58.

[22] Murphs D. Sarcos to produce US Army's exoskeletons in 2008.Available from: http://www.engadget.com.

[23] Walsh CJ, Pasch K, Herr H. An autonomous, underactuated exoskeleton for load-carrying augmentation. In2006 IEEE/RSJ International Conference on Intelligent Robots and Systems 2006 Oct (pp. 1410-1415). IEEE.

[24] Walsh CJ, Paluska D, Pasch K, Grand W, Valiente A, Herr H. Development of a lightweight, underactuated exoskeleton for load-carrying augmentation. InProceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006. 2006 May 15 (pp. 3485-3491). IEEE.

[25] Valiente A. Design of a quasi-passive parallel leg exoskeleton to augment load carrying for walking. Massachusetts Inst of Tech Cambridge media lab; 2005 Aug.

[26] Kawamoto H, Sankai Y. Power assist system HAL-3 for gait disorder person. InInternational Conference on Computers for Handicapped Persons 2002 Jul 15 (pp. 196-203). Springer Berlin Heidelberg.

[27] Kawamoto H, Lee S, Kanbe S, Sankai Y. Power assist method for HAL-3 using EMG-based feedback controller. InSystems, Man and Cybernetics, 2003. IEEE International Conference on 2003 Oct 5 (Vol. 2, pp. 1648-1653). IEEE.

[28] Lee S, Sankai Y. Power assist control for leg with hal-3 based on virtual torque and impedance adjustment. InSystems, Man and Cybernetics, 2002 IEEE International Conference on 2002 Oct 6 (Vol. 4, pp. 6-pp). IEEE.

[29] Hayashi T, Kawamoto H, Sankai Y. Control method of robot suit HAL working as operator's muscle using biological and dynamical information. In2005 IEEE/RSJ International Conference on Intelligent Robots and Systems 2005 Aug 2 (pp. 3063-3068). IEEE.

[30] Lee S, Sankai Y. Power assist control for walking aid with HAL-3 based on EMG and impedance adjustment around knee joint. InIntelligent Robots and Systems, 2002. IEEE/RSJ International Conference on 2002 (Vol. 2, pp. 1499-1504). IEEE.

[31] Kawamoto H, Kanbe S, Sankai Y. The Natural Frequency-Based Power Assist Control for Lower Body with HAL-3. InProc. of 12th IEEE Workshop on Robot and Human Interactive Communication (ROMAN2003) 2003.

[32] Yamamoto K, Hyodo K, Ishii M, Matsuo T. Development of Power Assisting Suit for Assisting Nurse Labor. JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing. 2002;45(3):703-11.

[33] Yamamoto K, Ishii M, Hyodo K, Yoshimitsu T, Matsuo T. Development of power assisting suit (miniaturization of supply system to realize wearable suit). JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing. 2003;46(3):923-30.

[34] Yamamoto K, Ishii M, Noborisaka H, Hyodo K. Stand alone wearable power assisting suit-sensing and control systems. InRobot and Human Interactive Communication, 2004. ROMAN 2004. 13th IEEE International Workshop on 2004 Sep 20 (pp. 661-666). IEEE.

[35] Ekkelenkamp R, Veneman J, Van der Kooij H. LOPES: Selective control of gait functions during the gait rehabilitation of CVA patients. In9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005. 2005 Jul (pp. 361-364). IEEE.

[36] Veneman JF, Kruidhof R, Hekman EE, Ekkelenkamp R, Van Asseldonk EH, Van Der Kooij H. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2007 Sep;15(3):379-86.

[37] Liu X, Low KH, Yu HY. Development of a lower extremity exoskeleton for human performance enhancement. InIntelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on 2004 Sep 28 (Vol. 4, pp. 3889-3894). IEEE.

[38] Liu X, Low KH. Development and preliminary study of the NTU lower extremity exoskeleton. InCybernetics and intelligent systems, 2004 IEEE conference on 2004 Dec 1 (Vol. 2, pp. 1243-1247). IEEE.

[39] Pratt JE, Krupp BT, Morse CJ, Collins SH. The RoboKnee: an exoskeleton for enhancing strength and endurance during walking. InRobotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on 2004 Apr 26 (Vol. 3, pp. 2430-2435). IEEE.

[40] ReWalk – for institutional and personal use [Internet].Available from: http://www.argomedtec.com.

[41] Krut S, Benoit M, Dombre E, Pierrot F. Moonwalker, a lower limb exoskeleton able to sustain bodyweight using a passive force balancer. InRobotics and Automation (ICRA), 2010 IEEE International Conference on 2010 May 3 (pp. 2215-2220). IEEE.

[42] Biomechanics of walking (gait) [Internet]. Available from: http://www.footeducation.com.

[43] Ground reaction force [Internet].Available from: http://www.answers.com.

[44] Ground Reaction Force [Internet].Available from: http://moon.ouhsc.edu.

[45] Brockway JM. Derivation of formulae used to calculate energy expenditure in man. Human nutrition. Clinical nutrition. 1987 Nov;41(6):463-71.

[46] Donelan JM, Kram R, Kuo AD. Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. Journal of Experimental Biology. 2002 Dec 1;205(23):3717-27.

[47] Van den Bogert AJ. Exotendons for assistance of human locomotion. Biomedical engineering online. 2003 Oct 14;2(1):1.

[48] Kirtley C.CGA normative gait database. Hongkong Polytechnic University.

[49] Linskell J. CGA normative gait database. Limb Fitting Centre‖, Dundee, Scotland.

[50] Winter A.Gait data [Internet]. Int. Soc. of Biomechanics. Available from: http://guardian.curtin.edu.au/org/data.

[51] Vukobratović M, Potkonjak V, Babković K, Borovac B. Simulation model of general human and humanoid motion. Multibody System Dynamics. 2007 Feb 1;17(1):71-96.

[52] Zatsiorsky VM, Seluyanov VN, Chugunova LG. Methods of determining mass-inertial characteristics of human body segments. Contemporary problems of biomechanics. 1990 Dec 1;272:291.

[53] Kamen G.Electromyographic kinesiology. Res. Methods in Biomechanics. Champaign, IL, Human Kinetics Publ., 2004.

[54] Reaz MB, Hussain MS, Mohd-Yasin F. Techniques of EMG signal analysis: detection, processing, classification and applications. Biological procedures online. 2006 Mar 23;8(1):11-35.

[55] Sy AC, Baldovino RG, Bugtai NT.Experimental design and analysis on factors determining bicep electromyography (EMG) signal behavior. Springer LNEE 2016.

[56] Sy AC, Baldovino RG, Bugtai NT. A fuzzy-based dynamic threshold algorithm for motion intention detection system for upper-limb electromyography (EMG) signal characterization. ICBER 2016, Osaka, Japan.

[57] Chen G, Guo Z, Yu H. Mechanical Design and Evaluation of a Novel Knee-Ankle-Foot Robot for Rehabilitation. InASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2015 Aug 2 (pp. V003T14A015-V003T14A015). American Society of Mechanical Engineers.

[58] He H, Kiguchi K. A study on emg-based control of exoskeleton robots for human lower-limb motion assist. In2007 6th International Special Topic Conference on Information Technology Applications in Biomedicine 2007 Nov 8 (pp. 292-295). IEEE.

[59] Ferris DP, Lewis CL. Robotic lower limb exoskeletons using proportional myoelectric control. In2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society 2009 Sep 3 (pp. 2119-2124). IEEE.

[60] Aguirre-Ollinger G, Colgate JE, Peshkin MA, Goswami A. Active-impedance control of a lower-limb assistive exoskeleton. In2007 IEEE 10th International Conference on Rehabilitation Robotics 2007 Jun 13 (pp. 188-195). IEEE.

[61] Yang Z, Gui L, Yang X, Gu W. Simulation research of exoskeleton suit based on neural network sensitivity amplification control. In2008 Chinese Control and Decision Conference 2008 Jul 2 (pp. 3340-3344). IEEE.

[62] Xiuxia Y, Gui L, Zhiyong Y, Wenjin G. Lower Extreme Carrying Exoskeleton Robot Adative Control Using Wavelet Neural Networks. InFourth International Conference on Natural Computation (ICNC) 2008.

[63] Yang Z, Zhu Y, Yang X, Zhang Y. Impedance control of exoskeleton suit based on adaptive rbf neural network. InIntelligent Human-Machine Systems and Cybernetics, 2009. IHMSC'09. International Conference on 2009 Aug 26 (Vol. 1, pp. 182-187). IEEE.

[64] Pratt J, Chew CM, Torres A, Dilworth P, Pratt G. Virtual model control: An intuitive approach for bipedal locomotion. The International Journal of Robotics Research. 2001 Feb 1;20(2):129-43.

[65] Pratt J. Virtual model control of a biped walking robot. Leg Laboratory, MIT 1995.

[66] Bosscher P, LaFay E. Haptic cobot exoskeleton: concepts and mechanism design. InASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2006 Jan 1 (pp. 867-876). American Society of Mechanical Engineers.

[67] Dick J, Crapuchettes B. Servo-Assisted Lower-Body Exoskeleton With a True Running Gait. InDAPRA Workshop on Exoskeletons for Human Performance Augmentation (EHPA) 2000 Mar 1.

[68] Fleischer C. Controlling exoskeletons with EMG signals and a biomechanical body model (Doctoral dissertation, Scuola Superiore Sant'Anna).

[69] Baniqued PD, Baldovino RG, Bugtai NT. Design considerations in manufacturing cost-effective robotic exoskeletons for upper extremity rehabilitation. InHumanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM), 2015 International Conference on 2015 Dec 9 (pp. 1-5). IEEE.

[70] Tsuge BY, Plecnik MM, McCarthy JM. Homotopy Directed Optimization to Design a Six-Bar Linkage for a Lower Limb with a Natural Ankle Trajectory. Journal of Mechanisms and Robotics. 2015 Aug 15.

[71] Jamisola RS, Kormushev P, Roberts RG, Caldwell D. Task-Space Modular Dynamics for Dual-Arms Expressed through a Relative Jacobian. Journal of Intelligent and Robotic Systems, vol. 83, no. 2, pp 205–218, 2016. Springer.

[72] Jamisola RS, Roberts RG. A More Compact Expression of Relative Jacobian Based on Individual Manipulator Jacobians. Robotics and Autonomous Systems, vol. 63, pp. 158-164., 2015. Elsevier.

[73] Lee J. Chang PH, Jamisola RS. Relative Impedance Control for Dual-Arm Robots Performing Asymmetric Bimanual Tasks. IEEE Transactions on Industrial Electronics, vol. 61, no.7, July 2014, pp. 3786-3796.