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Energy Efficiency of Gait Rehabilitation Robot: A Review*

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Abstract— **Gait rehabilitation robots have been reported to reduce impairment and regain functional abilities of gait disorder significantly. While energy efficiency is essential in the process of gait rehabilitation, few gait rehabilitation robots can achieve it. This paper aims to emphasize the importance of energy efficiency on the development of gait rehabilitation robots and conduct a view of rehabilitation training approaches as well as robots. Gaps and conflicts in traditional rehabilitation robots are analyzed based on the rehabilitation requirements and energy efficiency. While related research in reduction on energy consumption of human and optimization of human with device together during walking, is summarized. Finally, we discuss and highlight the future directions regarding the energy-efficient feature in gait rehabilitation robots.**

I. Introduction

Humans overcome the considerable anatomical and functional threshold, to evolve from quadrupedalism to bipedalism which is not an energy-efficient style and has taken almost 7 million years to regain energy efficiency [1]. Humans have been evolved well-suited to walk in a manner that conserves energy now [2]. Our inherent ability of walking coordination is updated during the whole lifetime [3], and adapt to new walking conditions quickly in an energy efficient way [4]. Walking is a specific task in human activities, to use a repetitious sequence of limb motion to move the body forward while simultaneously maintaining stance stability. Gait dysfunction is a deviation from normal gait, which is caused by problems in the nervous system or the musculoskeletal system [5]. Patients with a central neurological lesion result in spastic paralysis. The most common causes of spastic gait are neurological disorders such as stroke, incomplete spinal cord injury (SCI), cerebral palsy (CP), brain injury, and multiple sclerosis.

Deviations from the normal walking pattern will result in additional energy expenditure and increased muscular effort [6]. The increasing of net energy expenditure of walking is around 70% compared with healthy individuals, Comorbidity with several side-effects [7] contributes to increasing the risks of various cardiovascular diseases, cancers and diabetes mellitus. Therefore, available information on energy cost should be taken into consideration in the evaluation of exercise interventions and development of walking aids. Robot-assist gait training (RAGT) is a good choice in specific and repetitive rehabilitation [8]. Numerous robotic gait trainers have been developed in academia and industry, based on the difference of functional ambulation categories (FAC) and pathology rehabilitation stages [9]. However, based on recent research, only one soft robotic exosuit has been reported as having potential to achieve energy-efficient during gait rehabilitation [10].

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II. Gait Rehabilitation Robot

A. *Gait Rehabilitation Training*

Gait rehabilitation training is a process of neurological rehabilitation, and neural plasticity is the basis of rehabilitation [11]. Huge amounts of practice is a baseline principle to improvement [12]. Only a large amount of practice or repetition alone is hard to get the ideal outcome [13]. Training practice needs to be task-related to produce representational plasticity in motor cortex [14]. Training with a skill acquisition session shows the better performance [15]. General motor learning principles are hypothesized to still be valid for motor recovery [16]. Motor learning theories have driven the development of gait rehabilitation. Conventional rehabilitation can be categorized into three approaches:1) Compensatory approach is effective in functional recovery, but can cause reduction of joint range and long-term pain [17]. 2) Neuro-facilitatory approach: Bobath concept is a representative and widely adopted post-stroke physiotherapy approach in Europe. Training and application of the therapy are experience-based [18]. 3) Task-specific repetitive approach, which has proven that repetition plays a major role in inducing and maintaining brain changes [19]. The daily practice of task-specific motor activities is more efficient on the reorganization of the adult primary motor cortex rather than on repetitions alone [20]. Task-specific training is more effective than Bobath training for acute patient [21]. There is growing evidence supporting that task-specific repetitive training within physical therapy and robotic therapy can improve motor performance for patients with neurological lesions [22]. Robotic gait rehabilitation is a better solution because it is precise and tireless and can quantitatively assess the effectiveness of gait recovery with high accuracy [23].

B. *Analysis of Gait Rehabilitation Robot*

RAGT contains both top-down and bottom-up approaches [24], and has an innate advantage in intensive, specific and repetitive tasks; which is more effective in specific pathology stages with certain severity of impairments. Since the performance and characteristics of gait disorder vary in different stages [25], the focus of assistance varies in different groups in terms of specific rehabilitation requirements, shown in Figure 1. Walking ability can be evaluated by FAC. Severity impairment varies in the same stage and has great influence on machine constriction, training intensity and motivation [9]. The rehabilitation process toward regaining meaningful mobility have specific requirements and goals in different phases. The trend is similar but also has overlap [26]. Based on mobility, gait rehabilitation robots (GRRs) can be allocated to two categories: stationary gait rehabilitation robots (SGRRs) and mobile gait rehabilitation robots (MGRRs). The focus varies from motion enhancing, to stance supporting, to balance training. The human-machine constriction shows a downward trend. The training motivation of patients shows an upward trend which may make gait training more effective.

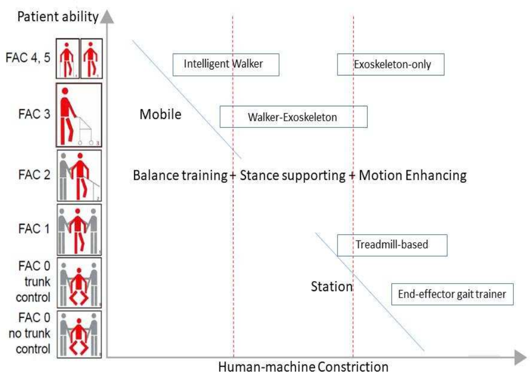

Figure 1. Analysis of Robotic Gait Training and Training Strategy

SGRR is usually an obvious choice for patients demanding stringent requirement for safety, which is relatively easily ensured [27]. Treadmill-based gait training robots (TMGRs) induce an immediate alteration toward a more consistent and symmetric gait pattern [28]. TMGRs can provide greater stimulus for balance training [29], compared with over-ground physical therapy gait training, and both of them improve gait speed and related parameters [30]. However, step length symmetry ration and self-selected walking speed [31] can only be more beneficial for patients through over-ground training. A combination of over-ground training and body weight support (BWS) interventions is a good solution [32]. SGRR is reported to be non-ecological training [33], and the metabolic cost of patients and muscle activation is higher than over-ground training [34]. Besides, the fixed gait pattern makes it difficult to achieve a natural gait [35]. MGRR can help the patient walk on the floor which will be more natural and improve the motivation of the patient [36]. In the process of gait rehabilitation, patients must use more of their residual force to learn and coordinate movements, and use less efforts to neutralize the gravity [37]. The mechanism of BWS is essential and effective for the gait rehabilitation in terms of temporal-spatial parameters [38]. Furthermore, the safety and falling protection should be ensured during training [36], which is also a big challenge for wearable exoskeleton [39]. Walker systems can maintain mobility and safety [40], and lead to overall reduction of spatial-temporal parameters, without modification in cadence-speed and stride length-speed relationships [41]. Furthermore, energy consumption of patients have increased significantly, when compared with independent walking and assisting with a walking stick [42]. Most actuated mobile gait trainers originate from passive ones. An additional power source can be equipped on the walker for forward propulsion [43]. In some cases, a powered lower limb exoskeleton for assisting the leg swing, or pelvic assistance manipulator with an additional power source and mass, is used to provide more control of the trunk and legs. Significant constraint has been imposed, but generates asymmetries in lower limb kinematics and muscle activity [44]. A systematic review has investigated the energy consumption in SGRR and wearable exoskeletons [45]. The metabolic cost of patients under conditions of robotic assistance is lower than without any assistance but still tremendously high compared with healthy subjects with robotic assistance. Walker-based has potential to achieve greater energy efficiency compared with other robotic aids [46]. The energy efficiency of wheeled locomotion is eight times higher than ordinary crawl gait [47], meaning that MGRRs have more potential.

III. Recent Advances in Energy-Efficient Devices

A device can be classified as powered or unpowered, and the powered one always has additional energy source. It can also be classified as tethered or untethered. Untethered is autonomous with all of the mass carried by the users.

A. *Recent Designs to Reduce Metabolic Cost of Walking*

In 2013, Philippe M. was first to develop a powered and tethered exoskeleton, using off-board pneumatic pumps and valves to replace work of human joints by exoskeleton work [48]. This is in terms of actuation timing during plantarflexion phase of gait, achieving 6% reduction in the metabolic cost of human walking. In 2014, Luke M. was the first to develop a powered and untethered exoskeleton. The device consists of a winch actuator and fiberglass struts to provide mechanical power during plantarflexion phase of gait considering actuation timing, reducing the metabolic cost of walking by 6-11% when compared to not wearing the device. In load carriage, a 5-10% improvement when wearing a 23kg vest was shown [49]. The biomechanical walking mechanism is explained in 2016 [50]. In 2017, Louis N. A. works with C. J. W. et al. to develop a powered and tethered exosuit which is lightweight and soft [51], to supplement the paretic limb's residual ability to generate both forward propulsion and ground clearance for stroke patients. The device has contributed to a reduction in the energy cost of walking which is equivalent to a 32 ± 9% reduction in the metabolic burden associated with post-stroke walking, while relatively low assistance is delivered to patients [10]. The relationship between assistance magnitude and the metabolic cost of walking while changing the wearer's gait mechanics has been explored: with increasing exosuit assistance, net metabolic rate continually decreased within the tested range, where the peak moment applied at the ankle joint was varied from about 10 to 38% of biological ankle moment, When maximum assistance was applied, reduced by 22.83 ± 3.17% relative to the powered-off condition [52].

Powered bipeds are based on passive designs and passive-dynamics, with small active power sources substituted for gravity. They make it possible to walk on level ground more naturally, yet with less control and energy than other powered robots [53].Passive-dynamic robots using passive dynamical properties of the body are designed to be more energy-efficient. Going even further, it is possible to harvest energy from human walking [54]. Steven H. Collins develops an unpowered device to show it is possible to use unpowered assistance to reduce metabolic cost by 4.6 to 9.8%. A mechanical clutch and spring have been used to fulfil the function of the calf muscles and Achilles tendon without interfering with other normal ankle functions. Furthermore, optimizing stiffness of spring, resulting in the change of metabolic rate has been explored in 2015 [55]. The unpowered assistance verifies the fact that level walking at steady speed requires no power input, all energy used in this activity is wasted. Simulation models with spring-loaded legs illustrate this fact [56]. During swing phase, the motion of the leg is only influenced by its own gravity [57]. Net metabolic rate during walking increased with load mass and farther distal location, and is not strongly affected by body mass distribution. Distal leg loads increased the metabolic rate required for swinging the leg. The increase in metabolic rate with more proximal loads attributable to a combination of supporting (via hip abduction muscles) and propagating the swing leg [58]. Inspired by previous research, Justin L. developed an unpowered exoskeleton, using spring-like properties of a pneumatic artificial muscle to provide timed torque at the push-off phase of the gait cycle in 2018 [59], muscle activities have been analyzed to show the effectiveness, but the relationship between muscle activity and metabolic rate remains imperfect.

B. *Optimization to Reduce Metabolic Cost of Gait*

Humans can continuously optimize energy cost during walking to achieve minimization of energy cost in a short time [60], and energy expenditure can be changed by step rate and step length during level walking [61]. When humans co-exist with an additional device as a reconstructive walking system, optimizing gait parameters and assistance of device, to reduce redundancy energy in human and machine system together, have been explored in several research regarding actuation timing and assistance patterns [62, 63].

In 2015, Wyatt Felt was the first to estimate the value of a physiological objective in real-time (Body-in-the-loop) for the online optimization of assistive robotic devices underlying Instantaneous Cost Gradient Search method [64]. The estimation of the Instantaneous Cost relies on surrogate function [65], which is adapted to match experimental measurements of energetic cost for fewer breaths requirement. This function is interpreted as a response surface that characterizes the energy-parameter relationship for optimization. In 2016, Jeffrey R. K. was the first to validate Felt's work by demonstrating on an actual assistive device[66], presenting the first ever example of Body-in-the-loop optimization, driven by objective physiological measurements to optimize the assistance of a device. The interaction was not based on a physical exchange between the robot and the user by forces and velocities, nor was it based on the exchange of information through a designated user interface or a neuro-interface. Instead, the proposed methods allowed a robot to directly react to the physiological state of the user, a state which may not always be obvious or may not even be consciously known to the user them self. In 2017, J. J. Zhang worked with Steven H. Collins to develop approaches to change the control of the device control in real-time to maximize human performance, which is Human-in-the-loop optimization. This optimizes device characteristics based on measured human performance, optimizing torque patterns from the exoskeleton to reduce metabolic energy consumption by 24.2±7.4% compared to no torque [67]. Zhang overcomes the limitations in previous works which building an approximation of the system takes time and the human changes during that time. Steady-state metabolic energy cost is estimated by fitting a first-order dynamical model, in one hour iterative process in real-time with a covariance matrix adaptation evolution strategy. In 2017, M. Kim and Y Ding worked with C. J. Walsh using Bayesian optimization to minimize the metabolic cost of human by optimizing walking step frequencies in unaided human, significantly reducing experimental times through parsimonious evaluation of walking conditions [68]. In 2018, Y Ding and M. Kim worked with C. J. Walsh to identify the peak and offset timing of hip extension assistance in participant-specific using a textile-based wearable device. Optimal peak and offset timing were found over an average of 21.4 ± 1.0min and reduction of metabolic cost during walking by 17.4 ± 3.2% compared with walking without the device, providing evidence for the hypothesis that individualized control strategies can offer substantial benefits over fixed control strategies [69].

IV. DISCUSSION

Natural gait is the most energy-efficient process, due to millions of years of evolution for bipedal walking. Gait parameter and energy consumption is optimized and stay at a stable level. The energy consumption in the process of gait is lower and stable, underlying Lyapunov Stability. Gait dysfunction can be considered as a kind of mutation in an unstable condition, leading to extra energy consumption. Gait parameters vary among different kinds of disorder conditions regarding pathology and FAC, while the energy consumption of walking is a potential feature to evaluate the walking ability. When people co-exist and coordinate with a robot as a reconstructive walking mechanism, we manually evolve our natural walking system to a new stage. The goals of gait rehabilitation are back to a new stable state, amending the parameter to a normal level while decreasing the energy consumption to a reasonable level.

Energy efficiency is important in the process of gait rehabilitation for patients. Robotic training has been reported as a good choice for rehabilitation. Few existing rehabilitation robots can achieve the energy economy, even for healthy subjects. For a specific person, gait parameter and energy consumption during walking stay stable in natural phase, and both of them are changed with gait disorders in the process of rehabilitation. More energy will be used to re-learn and coordinate movements, leading to a higher metabolic cost. Furthermore, both individual factors and non-individual factors will affect gait parameters and energy consumption of subjects. Whilst patterns of gait are proposed to be amended when a specific subject coordinates with additional devices in the rehabilitation process, comorbidity can cause extra energy consumption. Meeting the requirements of rehabilitation while considering the reduction of energy consumption is a challenge for the development of aids. In robotic gait rehabilitation, gait parameters will be influenced by assistive devices both for normal and disorder gait. While gait parameters will grade from disorder status to health status, the energy consumption will be changed at the same time.

A. Energy Efficiency in Robotic Gait Rehabilitation

When defining requirements for any walking assistance, it is important to maximize the user's metabolic benefit resulting from the assistance device while limiting the metabolic penalty of carrying the system's mass [70]. Most of the existing mechanisms in RAGT will increase certain mass and constraints for patients, which will increase the cost of metabolic energy and make gait correction difficult. Wearable robotic devices have been shown to substantially reduce the energy expenditure of human walking [69] since metabolic energy used during walking can be partly replaced by power input from robotics [71]. However, it is possible to reduce the metabolic rate without providing an additional energy source [55, 72]. In a gait cycle, redundant energy in the muscular-skeletal system will be harvested and transferred to active assistance in time. The damped system will be cooperated with muscle-skeleton to storage and release the redundant energy. Energy flow show in Figure 2.

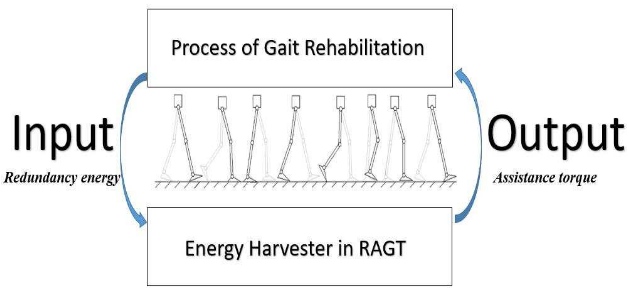

Figure 2. Energy Flow during Gait Rehabilitation

To achieve a high energy efficiency, the assistive mechanism should have the potential for energy harvest. Redundancy exists at many levels, including task, subject, etc. [73]. There are several potential approaches proposed to try to achieve the goals by understanding the natural walking mechanism of the human.

- In terms of human musculoskeletal system, redundant energy in human gait can be harvested, while a higher efficiency device can be used reasonably to replace the partial function of human gait.
- In terms of walking task, gait is a periodic and symmetrical process for specific tasks. Energy is harvested by neutralizing the gravity in a gait cycle and transferred to forward propulsion.

B. Accelerate the Evolution to Regain Energy-efficiency

Our natural walking mechanisms have been adapted to the specific task through years of evolution, fulfilling the specific task while realizing energy-efficiency. Neutralizing the gravity, and moving mass forward are two main works regarding the conservation of energy. The human body can be simplified as a mechanism; the energy expenditure of the musculoskeletal system and nerves can be treated as internal work. The external work refers only to work being done with the environment; the input is the metabolic cost, and the output is mechanical work. The energy efficiency has achieved in normal walking. Show in Figure 3 of green box.

When the natural mechanism is in disorder, the additional mechanism will be added to reconstruct the new walking mechanism. The work interaction between the natural mechanism and additional mechanism can be treated as internal work, while the external work of a new walking mechanism refers only to reactions with the environment. Show in Figure 3 red box. The energy efficiency in the process of gait rehabilitation has been reported pretty low in previous research. The connection between the change of gait parameter and energy consumption is the key to optimization.

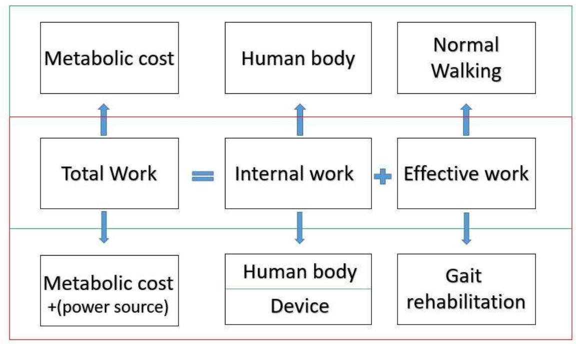

Figure 3. Energy Efficiency in Different Walking Conditions

In gait rehabilitation, the gait disorder will cause the difference of time-varying dynamic. The perturbations of gait patterns in new walking systems, on the process of motor adaptation, will increase metabolic cost [74]. The coordination of a movement is the process of mastering redundant degrees of freedom of the moving organ [75]. It is necessary for a new walking mechanism to adapt to a specific task quickly, especially for rehabilitation. Energy cost is a way to understand how interactions between device and gait parameters underlay motor control and learning, which can explain the resolution of redundancy with well-practiced specific tasks and unfamiliar environments, or for unfamiliar tasks [76]. In robotic gait rehabilitation, it is a kind of process for motor control for the specific task and motor learning in no-steady-state. The redundant energy will appear in different situation.

- The redundant energy in the musculoskeletal system of the human during normal walking.
- The redundant energy in the new walking system of a human coexisting with a robot during rehabilitation.

For RAGT, the process of gait rehabilitation is a specific task, and the redundancy in the new mechanism system can be changed through energy optimization. The goal of the optimization is to reduce the redundant energy in a human and robot walking system. Gait parameters in patients need to be amended, while the assistance of the device (torque pattern and timing) will be changed to adapt to a new status in a short time to achieve energy-efficiency. However, the coordination of the human is the baseline for the optimization, which means the performance of the human should be maximum while the total energy cost should be minimum at the same time. The improvement in the efficiency of the human-machine system as a whole can be remarkable given the apparent optimality of human gait to optimize the new walking system. Despite individual factors for customized design, optimizing device characteristics [67] by measured human performance could lead to improved designs.

V. Conclusion

Energy efficiency is an important feature in gait rehabilitation and also an essential criterion for the evaluation of walking ability as well as the development of the robotic aids. More, it is possible to harvest energy from the motion of humans and from a specific task of gait in rehabilitation. Optimizing redundant energy in human and machine system together to minimize the energy expenditure of humans and make the device contribute most, may be another potential strategy to guide gait rehabilitation with robots. The connection of energy consumption and change of the gait parameters are essential to understanding the computational model of motor control and motor learning in the process of gait rehabilitation.

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