Experimental Investigation on Adaptive Controlled GAIT Rehabilitation Robots

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Abstract— Over the rapid developments in mechatronics field, number of robotic platforms are emerged in medical field particularly in GAIT rehabilitation treatment targeted to recover the cardio vascular patients with acute neurological defects. Robotics Assisted Treadmill Exercise (RATE) is well known and efficient GAIT technique for the patient recovery. This work aims to develop a novel based adaptive controlled RATE, targeted to provide optimal exercise intensity for patients by feedback from oxygen uptake rate along with the heart rate with focus on impulse and ramp tracking. The proposed controller has communicate with feedback system for control of mechanical work rate which takes its target work rate from the automatic oxygen uptake control loop. This work also compares the efficiency and clinical feasibility of Adaptive Controlled – RATE with the Feedback controlled – RATE. Results of adaptive control of oxygen uptake profiles and disturbance rejection tests by impulse tracking demonstrated the technical feasibility and accuracy of the approach. The approach presented here provides adaptive control of exercise intensity during RATE by biofeedback and voluntary adaptation of the hip and knee forces by the individual.

Key words: GAIT Rehabilitation, Adaptive Control, Robotics- Assisted Treadmill Exercise (RATE), Oxygen Profile & Adaption Algorithm

I. INTRODUCTION

Robotic assisted gait rehabilitation has been primarily adopted for efficient recovery after strokes and also depicts for the adaptation of cardiovascular problems with neurological defects. For the past few days, such complementary robotic devices show their well efficiency in cardiovascular rehabilitative treatments. Robotics-assisted treadmill exercise (RATE) provides the effective exercise training in individuals with serious neural disorders.

A desirable cardiovascular fitness supports better management of the condition and better performance in the activities of daily living. However, a study reports that feedback controlled RATE did not reach recommended levels for aerobic training, regardless of the device settings. This raises the question of how to specify and control exercise intensity to achieve a training effect. In this paper, it has been suggested that adaptive controlled RATE is technically feasible. Some more work has investigated with different intensity-related parameters including external mechanical work rate, oxygen uptake, ratings of perceived exertion, human metabolic work rate and different walking conditions. In the field of physiotherapy, it is recommended that the intensity of exercise be specified through oxygen uptake rate because of its most reliable and direct indication of total physical movements in the human body.

Oxygen uptake is the recommended and accepted standard parameter for the assessment of aerobic fitness and also to control the exercise intensity. It has previously been shown that feedback control of oxygen uptake during RATE is feasible for step tracking and ramp tracking tasks in able-bodied subjects. The design of feedback controllers for tracking of VO_2 ramp profiles has been predicted theoretically and evaluated in simulation. A method for estimating maximal aerobic capacity would be an important contribution to the design of fitness training and assessment protocols for RATE. A well-established method is incremental exercise testing (IET), where the exercise intensity should be increased ramp wise until the subject reaches the limit of functional capacity. The previous work extends the idea of direct feedback control of oxygen uptake profiles for RATE to ramp tracking. The controller is embedded within a human-in-the-loop feedback structure to allow the subject to perform volitional control of mechanical work rate.

The feedback controller calculates the target mechanical work rate for the human in the loop. So that the desired target oxygen uptake rate is achieved. This work aims to develop a novel based adaptive control, targeted to provide optimal exercise intensity for patients by feedback from oxygen uptake rate.

II. CLINICAL PERSPECTIVES

Stroke, also known as cerebrovascular accident (CVA), cerebrovascular insult (CVI), or brain attack, is when poor blood flow to the brain results in cell death. There are two main types of stroke: ischemic, due to lack of blood flow, and hemorrhagic, due to bleeding. They result in part of the brain not functioning properly. Signs and symptoms of a stroke may include an inability to move or feel on one side of the body, problems understanding or speaking, feeling like the world is spinning, or loss of vision to one side among others. Signs and symptoms often appear soon after the stroke has occurred. If symptoms last less than one or two hours it is known as a transient ischemic attack (TIA).

Gait training or gait rehabilitation is the act of learning how to walk, either as a child, or, more frequently, after sustaining an injury or disability. Physical therapists, or physiotherapists, generally help their patients with gait training. Gait training can take a number of forms, but repetition of the actual motions performed during walking is the most important factor. Parallel bars may be used to help with gait training, especially in the early stages when a patient is first learning or re-learning to walk. They involve a person walking between two handrails to support themselves, often with the therapist either helping to support the patient or physically moving the patient's legs. Gait trainer or other gait aids are also utilized.

Treadmill training, with or without a body-weight support, is an emerging therapy and is being used with stroke patients to improve kinematic gait parameters. These patients often present with significant gait deviations and body weight-supported treadmill training can provide an intense repetitive practice of a more natural gait pattern. Research has shown that a greater gain in independent walking ability is seen in hemi paretic stroke patients who participate in structured speed-dependent treadmill training compared to conventional training. Improvements in gait parameters included walking speed, cadence, stride length and Functional Ambulation Category scores. If the patient were capable of maintaining the speed safely and comfortably during the 10-second bout, it would then be increased by 10% in the next attempt, following the same work and recovery procedures. Research has shown that this form of gait training demonstrates a more normal walking pattern without the compensatory movements commonly associated with stroke. Although gait training with parallel bars, treadmills and support systems can be beneficial, the long-term aim of gait training is usually to reduce patients' dependence on such technology in order to walk more in their daily lives.

The Lokomat is a robotic exoskeleton worn by the patients during treadmill walking. Four motorized joints (two per leg) move the hip and knee. The actuators consist of ball screws connected to direct current (DC) motors. The legs are driven in a gait-like pattern along a fixed position-controlled trajectory. The device attaches to the thighs and shanks through padded straps. A passive parallelogram mechanism allows vertical translation of the patient’ torso, restricting lateral translation. The patient’ body weight is unloaded as needed through an overhead harness. The Lokomat is currently being used in dozens of research labs and clinics worldwide.

III. TECHNICAL PERSPECTIVES

A. Controller & Tuning

A proportional – integral – derivative controller (PID controller) is a control loop feedback mechanism (controller) commonly used in industrial control systems. A PID controller continuously calculates an error value as the difference between a measured process variable and a desired set point.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt}$$

B. PID - Tuning Circuit

The Good Gain method is a simple method which seems to give good results on the lab and on simulators. The method is based on experiments on a real or simulated control system. The procedure described below assumes a PI controller, which is the most commonly used controller function (more common than the P controller and the PID controller).

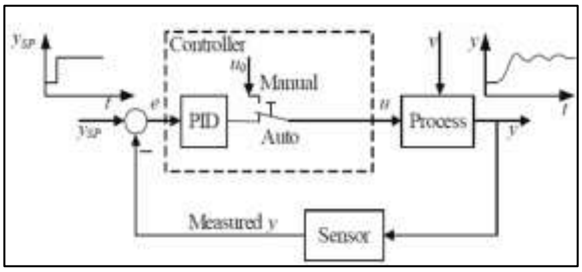

Fig. 1: Good Gain Method

1) Bring the process to or close to the normal or specified operation point by adjusting the nominal control signal u0 (with the controller in manual mode).
2) Ensure that the controller is a P controller with Kp = 0 (set Ti = ∞ and Td = 0).
3) Set the integral time Ti equal to Ti = 1.5T_{ou}. where T_{ou} is the time between the first overshoot and the first undershoot of the step response.
4) Check the stability of the control system by applying a setpoint step.
5) If you want to include the D-term, so that the controller becomes a PID controller, you can try setting Td as follows:

$$T_d = \frac{T_i}{4}$$

C. Adaptive Control

Adaptive Control covers a set of techniques which provide a systematic approach for automatic adjustment of controllers in real time, in order to achieve or to maintain a desired level of control system performance when the parameters of the plant dynamic model are unknown and/or change in time. In order to design and tune a good controller, one needs to:

1) Specify the desired control loop performances.
2) Know the dynamic model of the plant to be controlled.
3) Possess a suitable controller design method making it possible to achieve the desired performance for the corresponding plant model.

The dynamic model of the plant can be identified from input/output plant measurements obtained under an experimental protocol in open or in closed loop. One can say that the design and tuning of the controller is done from data collected on the system. An adaptive control system can be viewed as an implementation of the above design and tuning procedure in real time. The tuning of the controller will be done in real time from data collected in real time on the system.

D. Adaptation Algorithm

The parameter adaptation algorithm (PAA) forms the essence of the adaptation mechanism used to adapt either the parameter of the controller directly (in direct adaptive control), or the parameters of the adjustable predictor of the plant output. The development of the PAA which will be considered in this book and which is used in the majority of adaptive control schemes assumes that the “models are linear in parameters”.

$$y(t+1) = \theta^T \varphi(t)$$

Where θ denotes the vector of (unknown) parameters and φ(t) is the vector of measurements. This form is also known as a “linear regression”. The objective will be to estimate the unknown parameter vector θ given in real time y and φ. Similarly, for direct adaptive control it is assumed that the controller admits a representation of the form

$$y^{*}(t+1) = -\theta_c^{T}\,\varphi(t)$$

Where y* (t + 1) is a desired output (or filtered desired output), θ_c is the vector of the unknown parameters of the controller and φ(t) is a vector of measurements and the objective will be to estimate θ_c given in real time y* and φ. The parameter adaptation algorithms will be derived with the objective of minimizing a criterion on the error between the plant and the model. The parameter adaptation algorithms have a recursive structure.

$$\begin{bmatrix}\text{New estimated}\\ \text{parameters}\\ \text{(vector)}\end{bmatrix} = \begin{bmatrix}\text{previous estimated}\\ \text{parameters}\\ \text{(vector)}\end{bmatrix} + \begin{bmatrix}\text{Adaptation}\\ \text{Gain}\\ \text{(Matrix)}\end{bmatrix} \text{X} \begin{bmatrix}\text{Measurement}\\ \text{function}\\ \text{(Vector)}\end{bmatrix} \text{X} \begin{bmatrix}\text{Prediction error}\\ \text{function}\\ \text{(Scalar)}\end{bmatrix}$$

which translates to

$$\theta(t+1) = \theta(t) + F(t)\,\varphi(t)\,\nu(t+1)$$

IV. SYSTEM INVESTIGATION

A. *Subject Details*

Five inpatients after stroke were recruited from a rehabilitation centre in the north-western part of Tamilnadu (Chennai) and screened by the responsible ward physician and a cardiologist according to the selection criteria. The various characteristics of the considered inpatients are detailed in the table.

	Subject 1	Subject 2	Subject 3
Sex	Female	Male	Female
Age (Years)	47	62	48
Body Mass (Kg)	85	91	86
Body Height (cm)	168	173	169
BMI (Kg/m^2)	30.1	30.4	30.1
Diagnosis	Ischemic Stroke	Ischemic Stroke	Hemorrhagic Stroke
Affected Body Side	Right	Right	Left
Days Post Event	19	27	40
Medication	1,3,4	1,3,4,6,8	1,2,3,7
MMSE (0/30)	30	30	30
FAC (0/5)	3	1	2
CMSA Leg Score (1-7)	6	4	5
EBI at clinical admission (0/64)	59	53	55
EBI at first session (0/64)	62	58	59
EBI at clinical discharge (0/64)	64	63	62

Table 1: Subject Characteristics

B. *Exercise Testing Protocols*

The subject was instructed to vary the forces applied on the exoskeleton by volitional muscle activity and to keep the measured and visualized active work rate as close as possible to the target. At study entry, all included subjects completed a familiarization session with the RATE concept, which started by qualified and experienced physiotherapists adjusting the Lokomat system to provide a physiological gait pattern and to ensure that the subjects could walk comfortably.

Then, an initial test of decreasing BWS continuously by 5% per minute was implemented to define the minimal possible BWS level. After a break of at least 24 h, subjects then completed repeated constant load testing (CLT) and incremental exercise testing (IET) on separate days, with 48–72 hrs between the trials. All sessions were controlled for time of day. Subjects were instructed to avoid additional strenuous activity during participation in the study and not to consume food, alcohol, nicotine or caffeine at least 3 h prior to testing. Subjects were asked at the beginning of the first CLT and IET to increase their maximal voluntary effort during RATE within 30 s to define the maximal work rate (Pmax) for the subsequent tests. Walking cadence was fixed at 60 steps/min and individual BWS was consistent for all sessions. An experienced examiner performed all tests.

CLT was based on constant-intensity exercise separated into 4 phases:

1) Rest - subjects stood on the treadmill for 5 min with 0% BWS,
2) Passive - subjects walked passively with their individual BWS for 5 min,
3) Active - subjects actively contributed to the walking by pushing forward within the exoskeleton during the swing phase of each leg to reach the target work rate for 10 min,
4) Recovery – subjects walked passively with individual BWS for 5 min.

IET was based on progressive ramp exercise and separated into 4 phases:

1) Rest - subjects stood on the treadmill for 5 min with 0% BWS,
2) Passive - subjects walked passively with their individual BWS for min,
3) Active - subjects actively contributed to the walking by pushing forward within the exoskeleton during the swing phase of each leg to reach the target work rate,
4) Recovery - subjects walked passively with their individual BWS for 5 min.

The progressive ramp (active phase) was defined as a continuous slope aiming to the reach predefined Pmax in 10 min. Both test protocols followed strict termination criteria for CPET. Hip and knee joint forces and angles are measured in real time to allow calculation of the mechanical work rate (Pmech, solid line) and projection onto a screen in front of the subject. Individual target work rate profiles (P*mech, dashed line) are used to guide exercise intensity during robotics-assisted walking. The passive mechanical work rate (Ppassive) is evaluated before every session and subtracted from Pmech.

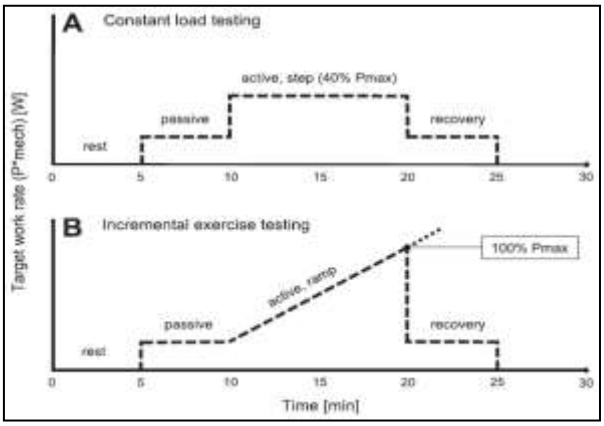

Fig. 2: Exercise Testing Protocol

The dashed line represents the target work rate (P*mech). The slope during incremental exercise testing was estimated such that the predefined work rate maximum (Pmax) was reached at 10 min during the active phase. When individual termination criteria were met the incremental phase was ended and P*mech set back to the passive level (recovery). where the formula was adjusted down to 70% of heart rate maximum for subjects on beta-blocker medications, pain or discomfort. Subjects rated their perceived exertion using the Borg rating of perceived exertion scale (RPE) (6 = no exertion at all, 20 = maximal exertion).

V. RESULTS & DISCUSSIONS

Three subjects were included (Table 6.1). The subjects were similar with regard to lesion, affected body side, time post stroke onset, and FAC. During CLT, all subjects reached a BWSmin level of 50%. Time constants of oxygen uptake kinetics for rest/passive and passive/rest steps during CLT were reasonable, but yielded low goodness of fit (R2) in most of the analyses. Step response kinetics for passive/active and active/passive steps were inconsistent throughout. Subjects generally yielded higher oxygen uptake values from rest to passive walking than from passive to active walking condition. The step change V_{O2} was associated with an increase in V_E during all CLT stages. However, HR and Rf did not increase consistently. For IET, the lowest achieved GF level (GFmin) ranged between 40-10%, and $V_{O2\ peak}$ values were mean. RER values were always below the termination threshold (≥1.15).

GET could not be analyzed due to inconsistent progression of breath-by-breath values. The 85% threshold of age predicted HR_{peak} values was not reached in any subject. HR, V_E, and Rf increased in all of the subjects. The procedure has found to be feasible and safe for individuals with severe motor impairment early after stroke. All subjects completed the four tests without any safety concerns. Subjects showed overall compliance, whereas data recording and processing during the experimental setup was successful for all procedures. Descriptive analyses were performed on all variables. Raw breath-by-breath data were processed using a bias free moving average filter over 15 breath. Outliers beyond 2 standard deviations between raw and filtered data were removed.

Almost all RMSEP values were belongs in safer region (≤ 11 W). The remarkable deviation of one subject (25.0 W), caused by a safety stop during CLT due to dis-coordination of the walking pattern, can be seen as a normal occurrence during RATE based on the challenges of the human-machine interaction mentioned above. These results confirm the feasibility of guiding cardiovascular exercise using a Adaptive-control structure within a robotics-assisted treadmill

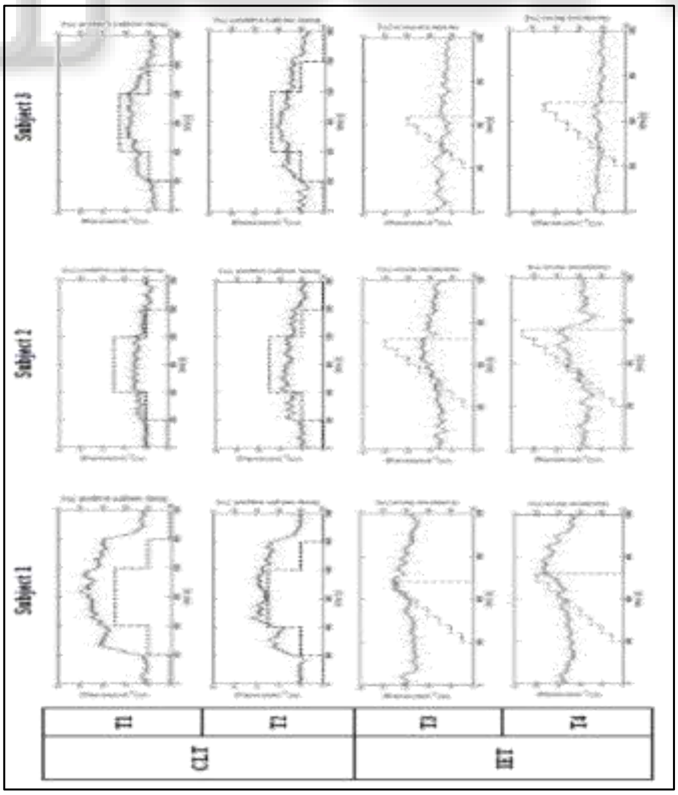

Fig. 3:

VI. CONCLUSION

A promising approach to overcome motor limitations while facilitating task-specific activity and cardiovascular stress is body weight supported treadmill training. Initial studies demonstrated feasibility and reliability for adaptive-controlled RATE (AC-RATE) to assess cardiovascular fitness and guide exercise intensity during CPET protocols soon after stroke. The next logical step is to evaluate AC-RATE in a pilot randomised controlled trial in order to assess the clinical efficacy and feasibility of the method for cardiovascular training during subacute stroke rehabilitation. This is relevant for the further development of the concept and the design of future large-scale trials.

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