ASSIST-AS-NEEDED CONTROL STRATEGY FOR UPPER-LIMB REHABILITATION BASED ON SUBJECT'S FUNCTIONAL ABILITY

BY

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ABSTRACT

Assist-as-needed (AAN) robotic rehabilitation therapy promotes neural plasticity and motor coordination through active participation in functional task. The technique significantly improves recovery of lost neural function following neurological impairment such as stroke. A key component of this strategy is to provide robotic assistance to the patients only as it is needed. Thus, accurate estimation of the patients' functional or movement ability (FA) is required to adequately evaluate the patients' need for robotic assistance or the amount of assistance torque to be provided. However, several strategies have shown inconsistencies in their estimation techniques and often significantly influenced by interferences and disturbances from the robotic device, making them unsuitable for clinical applications. The previous methods are also not related to clinical assessment scales in clinical practice. This study proposes an assist-as-needed (AAN) control strategy for robotic rehabilitation based on a new formulated Functional Ability Index (FAI) which adequately estimates patients' functional ability task. The formulated FAI starts with statistical normalization function (FAI_N) and then extended to apply a z-spline curve (*FAIs*) to estimate patient's movement ability based on the quality of movement (QoM) and the time score (TS) of the patient in each functional task. The approach is defined to be consistent with popular clinical method such as Wolf Motor Function Test (WMFT) and Action Research Arm Test (ARAT). A baseline low-level Linear Quadratic Gaussian (LQG) torque controller with integral action for robustness is integrated to the AAN controller to physically provide low-level torque assistance on the elbow and shoulder joint during reaching tasks. The overall strategy is automated by a hybrid finite state automaton to smoothly coordinate the patients' activities. Simulation and experimental study have been conducted to validate the proposed AAN control strategy with the newly formulated FAI. Eighteen patients completed the experimental study which involves two clinical tasks: a pick-and-place reaching task (Task 1) involving shoulder adduction/abduction movement and a table-to-mouth task (Task 2) involving elbow flexion/extension movement. Results showed that the proposed FAI algorithm could estimate patients' functional movement ability consistently with repeatability. And also allowing the proposed AAN control strategy to regulate the amount of torque assistance as needed, in accordance to the patients' functional ability and following the clinical assessment scales. The average torque assistance across trials for the mild and severely disabled patients were found in the range 3% - 6% and 42% - 47% for Task 1, respectively; and in the range 9% - 14% and 48% - 55% for Task 2, respectively; which are consistent with their FAI. The results show that the proposed AAN control strategy with the newly formulated FAI can successfully provide the assistance torque as needed to the patients in accordance with their patient's functional ability.

خلاصة البحث

تعتبر تقنية العلاج التأهيلي الذاتى باستخدام الربوت عند الحاجة مجالًا خصباً للبحث العلمى بغرض تعزيز مرونة الاعصاب والتنسيق الحركي بينها من خلال المشاركة الفعالة لاداء مهمتها الوظيفية بنجاح. وعليه فإن تقنية العلاج التأهيلي يمكنها أن تحسن بشكل ملحوظ من تنشيط الاعصاب لاداء وظائفها التى فقدتها من قبل نتيجة للضعف العصبى الناجم عن بعض الامراض أحياناً مثل السكتة الدماغية. ولهذا السبب فإن تقنية العلاج التأهيلي تعتبر أحد أهم المرتكزات الرئيسة لتنفيذ استراتيجية توفير المساعدة الآلية للمرضى ذوى الحالات الخاصة عند اللزوم. وبالتالي لتنفيذ هذه التقنية بنجاح، يلزم إجراء فحوصات دقيقة لمعرفة قدرة المرضى على مقدرتهم الوظيفية على الحركة ولتنفيذ ذلك يصبح إجراء تقييم كاف لحاجة المرضى إلى المساعدة الآلية بالإضافة لمعرفة عزم الدوران ضرورة ملحة ينبغى توفيرها لهم. وبالرغم من نجاح تلك التقنية الا ان العديد من الطرق/ الاستراتيجيات التى أستخدمت سابقاً كانت غير قادرة علي التناسق اليأ سائداً بينها خاصة التقنيات المستخدمة لتقديرعزم الدوران/الحركة العصبية نتيجة لتأثرها بشكل كبير بالتداخلات والاضطرابات الناجمة عن الجهاز الآلي المستخدم. ولهذا السبب أقترحت هذه الدراسة تقنية إعادة التأهيل المساعدة حسب الحاجة بناءاً على وظيفة خدد النشاط الوظيفي الجديدة باستخدام الربوت التي يمكنها تقدير نشاط حركة اعصاب المرضى بشكل كاف لاداء مهمة وظيفية الاعصاب فضلاً عن تكيفها مع المساعده الالية عند حاجة المرضى لها. لمعرفة ذلك لابد من تطبيق تقنية خدد النشاط الوظيفي الجديدة باستخدام منحنى البعد الثلاثي لتقدير قدرة حركة المريض على أساس جودة الحركة والفترة الزمنية للمريض في كل مهمة وظيفية يريد القيام بها. للقيام بالمهمة التى يريدها عند الزمن المحدد يتم بتطبيق وحدة التحكم في عزم الدوران الخطي بالتوافق مع الجهد المبذول للتوليف بين خدد النشاط الوظيفي الجديدة بالاستفاده من الحركة الناجمة عن تحديد عزم الدوران الناجم عنها للمساعده فى تحديد عزم الدوران ذو المستوى المنخفض على مفصلى الكوع والكتف معاً أثناء التحقيق/ الوصول إلى اداء مهمتها الوظيفية. نفذت الإستراتيجية الشاملة من خلال تطبيق آلية هجينية محدودة الحالة للتنسيق بين أنشطة المرضى بسلاسة مع ملائمة مهامهم. حوالى ثمانية عشر مريضاً قد اشتركوا فى هذه التجربه مع اكمالها علماً بأنها تضمنت مهمتين اساسيتين :اولاهما هى مهمة الوصول من الجدول إلى الفم والتي تضمنت على حركة الانحناء/ بسط الكوع ومهمة اختيار المكان، اما المهمة الثانية تضمنت حركة التقريب/ الاختطاف في الكتف. علماً بأنه يتم تكرار كل مهمة في تسع تجارب من اجل الحصول على أمكانية تطبيق التجارب السريرية اعتماداً على الحركة الوظيفية. أظهرت النتائج أن النموزج الرياضى المستخدم اعتماداً على لوغريثم خدد النشاط الوظيفي الجديدة الالى المقترح يمكنها بالطبع من تقدير قدرة الحركة الوظيفية

للمرضى بشكل متناسق مع تكرارها وبالتالى يمكن ان يسمح بتقديم المساعدة الآلية المناسبة للمرضى عند حاجتهم لاداء مهامهم/ وظائفهم. وبالتالي، يمكننا القول بأن وحدة التحكم هذه تتميز بالمساعدة عند عزم الدوران التى قدمت للمرضى عند الحاجة. ونتيجة لذلك تم العثور/الحصول على متوسط المساعدة عند عزم الدوران عبر تجارب المرضى شبه المعاقين وذوى الأعاقة الحرجة في مدى يتراوح بين 9٪ إلى 14٪ و 48٪ - 55٪ على التوالي للمهمة الاولى، مقارنة بالمهمة الثانية التى تتراوح في المدى المتوسط بين 3٪ - 6٪ و 42٪ - 47٪ على التوالي. وفى الختام، اظهرت النتائج ان الاستراتجية المقترحة ذات تقنية العلاج التأهيلي الذاتى باستخدام الربوت عند الحاجة مع قدرة الاطراف العليا الوظيفية للحركة المصاغة حديثا يمكن ان توفر بنجاح العزم المطلوب للمساعدة حسب الحاجة للمرضي وفقا لقدرة المريض الوظيفية.

APROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Signature .... Date ....

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AA	Abduction/Adduction
AAN	Assist As Needed strategy
ADL	Activities of Daily Living
AMAT	Arm Motor Ability Test
ARAT	Action Research Arm Test
CAHAI	Chedoke Arm and Hand Activity Inventory
DAQ	Data Acquisition
DOF	Degree of freedom
FA	Functional Ability
FAI	Functional Ability Index
FAI_N	Functional Ability Estimation Index using Normalization
FAI_S	Functional Ability estimation Index using z-spline function
FAS	Functional Ability Scale
FASF	Functional Activity Spline Function
FE	Flexion/extension
FIM	Functional Independence Measure
FMA	Fugl-Meyer Assessment of sensorimotor recovery after stroke
GAAN	Greedy Assist-As-Needed
GRBF	Gaussian Radial Basis Function
IMU	Inertial Measurement Unit
IIUM	International Islamic University Maaysia
K	optimal gain matrix
LL	lower limb
LQG	Linear Quadratic Gaussian
LUL	Lift Upper Limb
mAAN	minimal Assist-As-Needed
MAS	Motor Assessment Scale
MESUPES	Motor Evaluation Scale for Upper Extremity in Stroke subjects
MBA	Model Based Adaptive
N	The highest functional ability level
Nm	Newton Metre
OT	Occupational Therapy
pAAN	Progress Assist-As-Needed
PAP	Pick and Place
PID	Proportional Integral Derivative
pMAs	pneumatic muscle actuators
PS	Pronation/Supination
PT	Physical Therapy
QoM	Quality of movement
RMSE	Root Mean Square Error
ROM	Range of Motion
RUL	Right Upper Limb
SCI	Spinal Cord Injury
T	Trial

TS	Time score
TTM	Table to Mouth
UEFT	Upper Extremity Function Test
UL	Upper limb
WMFT	Wolf Motor Function Test

LIST OF SYMBOLS

τ	Torque
τ_static	Static Torque
τ_stiffness	Stiffness Torque
τ_dynamic	Damping Friction Torque
t	Sampling time
$\mathcal{F}_i$	Normalized functional ability
α	Alpha
β	Beta (stipulated time slot, 60s and 30s)
kHz	Kilohertz
zmf	z-spline Function
δ_{rms}	Root Mean Square Error
t_p	Time for the patient to complete the task
t_h	Time for the healthy subject to complete the task
X	Measurement indices
$\dot{q}$	Speed
$\dot{q}_h$	Speed of healthy subject
$\dot{q}_p$	Speed of patient
K_D	Decay gain matrix
$\emptyset_t$	Time scores
$\emptyset_p$	Quality of movement
zmf	z-spline function
t_{limit}	Maximum time given to complete the task
q	Joint angle position
q_d	Desired angles
q_{rms}	Quality of movement measured as root mean square
$q_{h_{rms}}$	Quality of movement of the healthy participant
$q_{limit_{rms}}$	Maximum root mean square that can deviate from the reference trajectory
a, b	Represent any interval on the continuous function
τ_{AAN}	Reference torque assistance
τ_0	Starting torque assistance
$\tau_f(q, \dot{q})$	Friction torque
I and $\dot{I}$	Motor current and the derivative of the current respectively
τ_u	Control input
L	Kalman gain
$\hat{\tau}$	Kalman estimate of the system states
τ_i	Integrator states
Q	Set of discrete mode/state
ε	Event that causes transition from one state to another
λ	maximum allowable range of motion for the task
F	Flag that signals the execution of a task
w_f	Fundamental frequency

u	Voltage
k_p	Proportional gain
b_0	Static friction torque
$b_1 sgn(\dot{q})$	Kinetic friction torque
$b_2(\dot{q})$	Damping friction torque
$\tau_s(q)$	Stiffness torque
s	Second
g	Gram
kg	Kilogram
π	Signal frequency
$^{\circ}$	Degree

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Stroke is the leading cause of disability world-wide (Al-Eithan, Amin, & Robert, 2011; Hatem et al., 2016). It significantly reduces the patients' ability and performance in carrying out activities of daily living (ADL) (Pilutti et al., 2011). Statistics show that about 80% of people with acute stroke manifest upper limb motor impairment are accompanied with reduced arm function (Rodgers et al., 2019). Even after the first four years after the stroke, about 50% will still have functional impairments (Rodgers et al., 2019). Regaining patients' functional ability after stroke is the primary focus of physical and occupational therapy (Mounis, Azlan, & Fatai, 2017). Early therapy after stroke usually includes passive exercise training to prevent muscle atrophy and relieve joint contractures (Nas, Yazmalar, Şah, Aydın, & Öneş, 2015). However, as the training progresses, active participation is encouraged to provoke neuroplasticity of the affected regions of the nervous system and to improve patient functional ability (Flachenecker, 2015; Pehlivan, Losey, & O'Malley, 2016).

Clinical studies have suggested that, for patients who have regained parts of their motor functions (Houwink, Nijland, Geurts, & Kwakkel, 2013), combination of rehabilitation treatment and voluntary efforts from the patients facilitates the recovery of motor ability faster and more efficiently (Muratori, Lamberg, Quinn, & Duff, 2013). Thus, assisting every movement of the patients is not beneficial compared to when they are actively involved in exercise (Billinger et al., 2014). Active training requires cognitive processing which stimulates neuroplasticity. Therefore, it achieves greater performance compared to movement training that did not encourage cognitive processing (Hötting & Röder, 2013; Looi et al., 2016).

Assist-As-Needed robotic therapy is currently a driving trend in robot-aided rehabilitation therapy (Blank, French, Pehlivan, & O'Malley, 2014) that emphasizes patient active participation (Hussain, Jamwal, Ghayesh, & Xie, 2016). Under the assistive scheme, the patient performs the prescribed task independently while the robot provides assistance to aid the patient only when it is deemed necessary, otherwise it withholds the assistance (L. Luo, Peng, Wang, & Hou, 2019). Some AAN schemes introduce a baseline minimal robotic assistance that is first provided to the patients to assist on the exercise. Then, the robot decreases the assistance according to the patients' need or movement ability, thus adapting the assistance according to the patient's functional capability (Rehmat et al., 2018).

However, the major challenges in this study are how to effectively determine the patients' movement/functional ability required to set the minimal robotic assistance, and also how to adjust this assistance consistently with changing patients' movement abilities (Frullo et al., 2017; Peng et al., 2018). Finding an effective Functional Ability Index (FAI) estimation strategy that is consistent and repeatable for a wide patients population and consistent with clinical procedures is still unresolved in AAN research (Mounis et al., 2017; Pehlivan et al., 2016). Several existing studies rely on the robot models to estimate patients' FAI. These techniques present several errors of estimation due to model uncertainties making them inconsistent for a wider patients' population. Thus, this study presents an ANN strategy to regulate robotic assistance based on a novel functional ability index (FAI) derived from a z-spline functional ability curve.

The formulation strategy starts with statistical normalization function FAI_N then extended to Z-spline function FAI_S. The input to the z-spline curve is based on the patient's quality of movement and time score in each functional task. They are important parameters in the conventional clinical procedures of estimation of functional ability including the Action Research Arm Test (ARAT) and Wolf Motor Function Test (WMFT). The FAI does not rely on robot models. It serves as input to a torque mapping algorithm coupled to a Linear Quadratic-Gaussian (LQG) control law which consequently varies the robotic assistance according to the subject's functional ability. The new FAI technique thus allows clinical procedure of FAI estimation to be automated in robotic therapy and consistent estimation over a wider patients' population.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

Assist-As-Needed (AAN) robotic therapy strategy is a method of robotic assistance and rehabilitation therapy that involves assisting a subject only when the subject is in need of that assistance. AAN can enhance motor plasticity and functional motor recovery in neurologically impaired subject. The determination of the subject's movement or functional ability is crucial in AAN robot-assisted therapy. However, this has been very challenging for many AAN based robotic applications. The accuracy of subject's movement/functional ability that is consistent for a wide range of subjects and in line with the clinical procedure are the important factors in AAN strategy. However, these issues are currently limiting the implementation of AAN robotic therapy in a real clinical setting. Gaussian radial basis function (GRBF) was previously used to estimate the patient's functional ability. However, the limitation of this approach is the reliance on the robot model in estimating the subject's capability. It is also well known that model errors always exist and can significantly excite the disturbance term, thus making it difficult to consistently and accurately estimate the subject's functional ability (Pehlivan et al., 2016). Different robot models would produce different functional ability estimating which will hinder an appropriate standardization of robotic assistance for therapy purpose. There are also less previous studies that have been done to correlate the robotic assessment with an actual clinical assessment scale to estimate subject's functional ability.

1.3 RESEARCH OBJECTIVES

The main objective of this work is to develop a new Assist-As-Needed control strategy based on the patient functional or movement ability estimation to enhance the effectiveness of AAN robotic therapy and to bridge the gap between robotic assistance and actual clinical procedures. The specific objectives are:

1. To formulate a new functional ability estimation index in line with the clinical assessment scales for upper limb rehabilitation system.

2. To develop a new AAN controller strategy to regulate the robotic assistance based on the newly formulated patient's functional ability estimation index.

3. To validate the proposed AAN control strategy with the formulated functional ability estimation index for upper limb rehabilitation system by simulation and experimental procedures.

1.4 RESEARCH METHODOLOGY

This research had been carried out in different stages as follow: