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Develop a wearable ankle robot for in-bed acute stroke rehabilitation

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Abstract—**Movement training is important in motor recovery post stroke and early intervention is critical to stroke rehabilitation. However, acute stroke survivors are actively trained with activities helpful for recovery of mobility in only 13% of the time in the acute phase. Considering the first few months post stroke is critical in stroke recovery (neuroplasticity), there is a strong need for movement therapy and manipulate/mobilize the joints. There is a lack of in-bed robotic rehabilitation in acute stroke. This study seeks to meet the clinic need and deliver intensive passive and active movement therapy using a wearable robot to enhance motor function in acute stroke. Passively, the wearable robot stretches the joint to its extreme positions safely and forcefully. Actively, movement training is conducted and game playing is used to guide and motivate the patient in movement training.**

I. INTRODUCTION

Training and exercise is important in neuroplasticity and motor recovery post stroke [1]. A recent Clinical Practice Guidelines [2] "recommend that rehabilitation therapy start as early as possible, once medical stability is achieved." Several studies suggested stroke rehabilitation should be initiated soon after stroke to achieve optimal results [3-5]. A recent study showed strong relationship between early admission to rehabilitation and improved functional outcome among the most severely impaired patients [6]. Another study found that interval between stroke onset and admission to rehabilitation was a predictor of achievement of rehabilitation potential among 258 patients recovering from first-ever stroke [7]. A shorter onset time was associated with improved functional outcome [8]. When attempting to determine factors that contribute to the improved functional outcomes that are associated with specialized stroke rehabilitation, the intensity of rehabilitation therapies is often cited as an important factor. For patients receiving enhanced early stage therapy, there was a significant 14 day reduction in length of stay [9]. Retrospective study of 4,988 patients (993 with stroke), evaluating the length of stay and functional improvement shows higher intensity of therapy was associated with shorter length of stay [10].

However, acute stroke survivors are actively trained with activities helpful for recovery of mobility in only 13% of the time and they are left alone in more than 60% of the time in early post-acute rehabilitation window [11]. Considering that early onset of rehabilitation interventions is strongly associated with improved functional outcome [12], there is a strong need for active movement therapy and manipulate/mobilize the joints early in acute rehabilitation. This project will seek a feasible solution which can meet this clinic need and deliver intensive and motivating robotic therapy intervention for better motor re-learning in acute stage to reduce therapist loads in repetitive practice tasks. This project will conduct combined passive stretching and active movement training with motivating games using a wearable robot to enhance motor recovery in acute stroke survivors.

II. CONCEPT MODEL

The presented stretching and active movement training can keep the joint mobile and potentially loosen the stiff joint, based on the novel intelligent stretching protocol [13-14], which adjusts the stretching velocity and torque based on the specific joint conditions and thus makes it more likely to be effective than existing devices such as the continuous passive motion (CPM) which moves at a constant velocity and orthotic devices which apply a constant spring load to the joint.

A difficulty with existing treatment of ankle deformity and spastic hypertonia in stroke is that the treatment may not be readily available to the patients, as acute patients post stroke is treated with movement therapy in only 13% of the time during their acute phase recovery [11]. Frequent treatment and exercise are needed for long term improvement. The robotic device will be designed to be wearable so that patients can use it conveniently while recovering in bed and the robot can implement treatment of experienced therapists with added precise control of the resistance torque and stretching velocity, which will likely make the stretching effective and make "experienced therapists" who can stretch precisely available to more patients post stroke.

The proposed wearable rehab robotic device not only stretches the spastic joint but also helps active movement training with assistance or resistance provided to the patient when needed. The games keep the subjects engaged, which is important in motor recovery (neuroplasticity).

Furthermore, the wearability and relatively low cost of the presented robotic device and its flexibility for multiple joints (e.g., ankle, elbow, wrist, and knee) will make it conveniently available to patients acutely post stroke for more frequent clinic and/or home uses to reduce hypertonia and improve motor control.

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III. MECHANICAL DESIGN

Physiological range of motion (ROM) and maximum allowed torques at ankle joint has been evaluated for an optimized design of the wearable system. As a high efficiency system, lighter weight is required for this wearable device. After testing, we expect to find the best powered actuator solution with lighter weight and enough power to stretch and assist patient's ankle joint.

The expected specification of the robotic system:

The Specification of the whole Motor Driven System	
Total weight	Less than 1.5kg
Nominal voltage	24v, 200w
Max. continuous speed	about 300 deg/sec
Max. continuous torque output	20Nm
Transmission structure	Simple, durable and cost-effective

We have compared several recent actuator solutions and transmission designs: rotating motor assembly, linear motor assembly and pneumatic artificial muscles. Finally we choose the rotating motor assembly solution as a cost-effective design. It still is a best low-cost solution comparing with others and can bring more productive benefits, such as low-cost assembling procedure for manufacturing, standard and reliable mechanical structure and simplified control design.

The feasibility of Maxon EC-Power Max Brushless motor series will be tested as the driven actuator in our mechanical design stage. It comes with smaller size, but can generate up to 7 Nm continuous torque with proper gear reduction box. Comparing with other rotating actuators, this motor and gear combination is an optimal solution for delivering a powerful joint stretching.

Based on clinical evidences, 7 Nm torque output may not be strong enough to stretch some adult patient's stiffer ankle joint, so a bevel gear mechanism with a certain gear ratio is chosen to allow both high torque output and back-drivability with our proposed control method. The bevel gear design also allows a more efficient measuring of the human joint through the motor system. In this design, we will not consider a worm gear transmission because it cannot perform the mechanical capacity of our desired back-drivability. As other solution of secondary mechanical transmission, the cable mechanism will be tested as another solution (Fig. 1). Therefore, a preliminary design of high efficiency actuator including mechanical part and the wearable brace will be expected and developed with lightweight (<1.5kg) and with up to 21 Nm continue stretching torque capacity (Fig. 2a). Additionally, a 50lb force sensor is added between foot brace and driven linkage beam to measure the joint resistance and robot assistance.

IV. DESIGN OF ROBOT-THERAPY FUNCTIONS

A key feature of the developed robot is being able to choose a proper training program/mode based on the specific impairment and recovery status of the patient (Fig. 3). The robot-assist control algorithms will be developed specifically with the following functional targets. Instead of a single passive stretching mode or single fully active/measuring mode, we focus on a combined robot-assisted treatment, because we believe it is essential for patients to be encouraged use of impaired limbs in early rehabilitative stage by providing assistance. Furthermore, the system could run safely under autonomous control while providing a powerful stretching/assisted force.

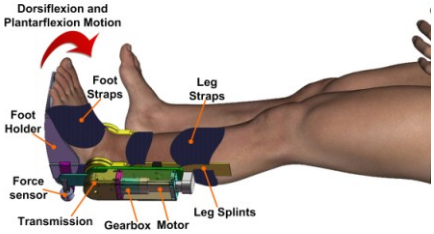


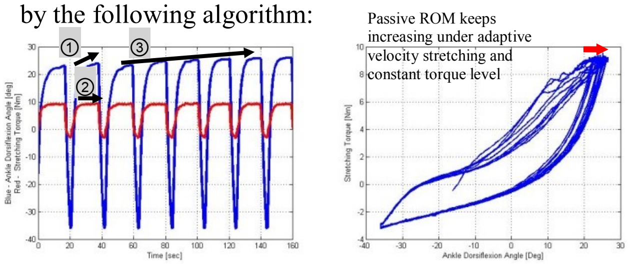
Fig. 1 Mechanical Design

1. Back drivable function: The device can sense the desired direction of the patient's joint movement and follow his/her moving freely so that the patient can move ankle without feeling the resistance from the device.
2. Assistive Active function: The device can detect the level of moving function of the patient and provide a certain assistive torque to help his/her to move to the desired target or provide a certain resistive torque to enhance his/her muscle.
3. Stretching function: The device can stretch the ankle safely and effectively with max 20 Nm torque output.

1) To conduct a safer and more effective joint stretching based on the ankle joint resistance by using force sensor

Based on an intelligent stretching strategy, the digital controller controlled the stretching velocity at ankle joint according to the resistance torque $M_{res}(t)$: Near the end of ROM, the stretching velocity slowed down gradually with increasing resistance torque, which was important for safe operation. Furthermore, the stretching did not stop until a pre-specified peak resistance torque was reached. In this way, the muscle-tendons involved were stretched strenuously and safely, which likely resulted in increased ROM. Once the specified peak resistance torque was reached, the device held the joint at the extreme position for a period of time (e.g., 10 sec during each cycle of the back-and-forth stretching), as used by an operator (therapist or others). In the middle of ROM, where the resistance was usually low, the device moved the joint quickly at higher velocities. As a safety precaution, both position and torque limits could be set by the operator using a touchscreen computer to communicate with the controller and they were monitored by the digital controller during the passive stretching. Specifically, for ankle joint, the control rules, shown in Fig. 2, were implemented in the digital controller to adjust the stretching velocity $V(t)$ every 0.5msec.

For example, the controller will be set with a maximum resistance torque limit. As this maximum torque limit is reached, the motor holds the ankle in position for a predetermined amount of time and then reverses the direction of the motor shaft such that the ankle is moved in the opposite direction. In addition, the controller determines the velocity of the movement, the velocity being inversely proportional to the resistance torque such that as the resistance torque $M_{res}(t)$ increases, the velocity decreases. Conversely, as the resistance decreases, the velocity increases. This inverse relationship is described by the following algorithm:



(a) (b)

Fig. 2 Typical angle-torque relationship curve under intelligent control.

M_{res} denotes the joint torque (red); M_p and M_n the positive and negative peak torques, respectively; θ_p and θ_n pre-specified positive and negative end of the ROM, respectively. θ_d the allowed further rotation beyond the position limits (Trend Arrow①). k the constant determining the scale of velocity reduction. Individual joint can be stretched strenuously by robot between two pre-specified peak torque limits (Trend Arrow ②). The passive ROM can be gradually increased under an adaptive stretching velocity (Trend Arrow① & ③)

$$V(t)=\begin{cases} 0, & \mathit{if}\ \left[(M_{res}^{k}(t)\geq M_p \ \ \mathit{or}\ \ \theta(t)\geq\theta_p+\theta_d) \ \ \mathit{and\ \ need\ \ to\ \ hold}\right] \\ -V_{\max}, & \mathit{if}\ \left[(M_{res}^{k}(t)\geq M_p \ \ \mathit{or}\ \ \theta(t)\geq\theta_p+\theta_d) \ \ \mathit{and\ \ have\ \ held\ \ long\ \ enough}\right] \\ \max\left(\dfrac{C}{M_{res}^{k}(t)},V_{\min}\right), & \mathit{if}\ \ 0<M_{res}^{k}(t)<M_p \\ \min\left(\dfrac{C}{M_{res}^{k}(t)},-V_{\min}\right), & \mathit{if}\ \ -M_p<M_{res}^{k}(t)<0 \\ V_{\max}, & \mathit{if}\ \left[(M_{res}^{k}(t)\leq -M_n \ \ \mathit{or}\ \ \theta(t)\leq\theta_n-\theta_d) \ \ \mathit{and\ \ have\ \ held\ \ long\ \ enough}\right] \\ 0, & \mathit{if}\ \left[(M_{res}^{k}(t)\leq -M_n \ \ \mathit{or}\ \ \theta(t)\leq\theta_n-\theta_d) \ \ \mathit{and\ \ need\ \ to\ \ hold}\right] \end{cases}$$

2) *Design Assistive-active training rehabilitation games*

Motor impairment is associated with both neural and peripheral biomechanical changes. After the certain intelligent passive stretching reduces the joint stiffness and muscle tone, the neural command may be able to better control the muscles and move the ankle. The wearable device will switch to backdrivable mode so that patients can move their ankle joints freely to match or track targets displayed on a computer monitor during the movement training. The movement training will be done through game playing and motivate the patients and enhance their motor relearning in an early stage.

The controller will measure the desired ankle position and the patient's current joint position to calculate the error vector, and the controller can potentially assist or resist the patient to play the game based on this error (Fig. 6).

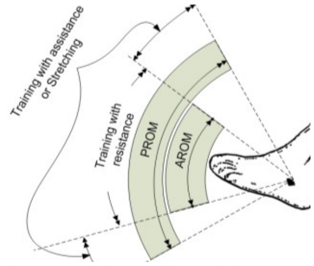


Fig. 3 Assistive-active training mode selection

The interactive games were developed for acute stroke in-bed training and be able to promote patients to watch their ankle motion feedback in a virtual reality scenario on a large touch screen monitor. They can drive a car or kick soccer balls. Additional sound or background music playing, and brightly colored graphics motivate patients to work harder and longer during a session. Virtual reality exercises are versatile, allowing an operator to select exercises and preset parameters for each patient. For improved rehabilitation, an operator can tailor a session by setting the range of motion and level of difficulty and selecting the training modes. Each game is conducted at a level customized for the individual patient. The setting for a game (active, active assistive, passive, and seldom resistive exercise) could be modified by the operator according to the subject's ability. Hence there is no excessive effort involved during the game playing. Moreover it moves within preset passive ROM and torque limits for safety. Besides it will not make an aberrant movement since it just moved along the machine guided trajectory even if the patient did not have proper control.

The level of assistance will be adjustable depending on joint recovery status. Once the participant mobility gets improved, the level of assistance will be decreased accordingly. If the participant can more independently complete the task with minimal assistance, the controller can even increase the level of resistance to challenge the participant and expedite the progress of rehabilitation.

V. EXPERIMENTS & CASE STUDY

1) *Protocol & Recruitment*

Four patients with acute post-stroke were referred by doctors in Rehabilitation Institute of Chicago-RIC to test the feasibility of the system and evaluate the designed Rehabilitation protocol. They were treated by using the wearable ankle system in bed. Due to the average length of stay for patients admitted in a stroke rehabilitation hospital is 14-16 days, they received 5 times per week, 40 minutes per time, up to 12 times treatment based on their inpatient rehabilitation schedule.

Each treatment session included passive stretching, active movement therapy and the protocol was as following: Assess daily biomechanical property changes (~5min), Intelligent passive stretching (~10min), Games related active movement training (~15 min, active/active-assistive/passive/rarely resistive movement), Intelligent passive stretching (~10min). The training task combination chosen by an operator according to the condition of the patients and the training posture was lying down with the knee extended and hip flexed slightly, as shown in Fig. 4.

Fig. 4 Experimental setup in a hospital setting: A patient wearing the device on left ankle and training in bed.

2) Results: Track neurological impairment and neuromuscular change and recovery status on the mechanical properties of the ankle quantitatively and accurately in an early rehabilitative stage

In an early rehabilitative training and decision stage:
1. <u>Tracking passive biomechanical properties by using the developed robot:</u> the passive biomechanical properties such as the passive ROM and the passive stiffness at the individual joints have been measured by position and force sensors. The properties measured from patients could be compared with that from the healthy subjects to determine the abnormality in the patient's ankle. While patient wear the device in bed, the passive biomechanical properties are measured during the passive ROM test. The joint stiffness will be calculated by the slope in the torque-angle curve. A subject under 3 levels (3, 5 and 7Nm) of stretching shows increasing ROM and repeatable stiffness trend (Fig. 5).

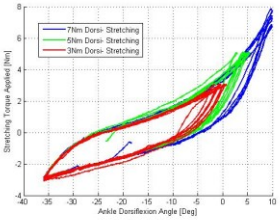


Fig. 5 The slopes of angle-torque relationship curve under passive stretching of different torque.

2. <u>Tracking active biomechanical properties of inpatients:</u> The wearable robot can assess neuromuscular performance of the patients during recovering stage through the game playing. The patients were asked to move his/her ankle joint actively with the assistive force/torque (red line), actual moving position (blue line) and desired training target (green line) monitored (Fig. 6). Active ROM, muscle strength (Fig. 7) could be measured to evaluate the impairments and recovering stage.

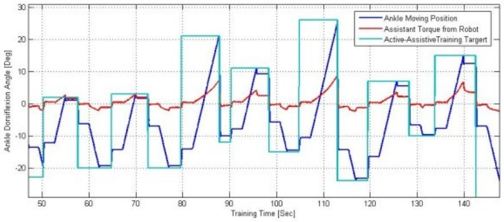


Fig. 6 The record of one participant during his game playing, while the controller detected the discrepancy between the targeted ankle position(green line) and the patient's joint position(blue line), the assistant torque(red line) was afforded by the device.

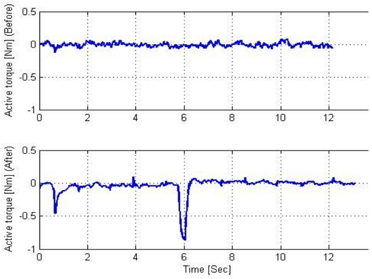


Fig. 7 Strength before and after treatment in an acute patient. No toque shown before but two toque peaks were seen after the treatment.

VI. DISCUSSION

Four patients satisfied with the wearing and operating of the device. The designed training protocol were carried out smoothly and well accepted by all participants. With analyzing of the collected data we can sensitively detect the change of active and passive biomechanical properties. In this study, we mainly focused on the discussion about the optimized functional design of wearable robot. The further research and clinical study are in progress. The present work is just our preliminary study. We are planning to recruit more inpatients and collect more experimental data to evaluate the reliability and feasibility of this wearable robot solution.

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