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Control design for a lower-limb paediatric therapy device using linear motor technology

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ABSTRACT

Background: Rehabilitation robots support delivery of intensive neuromuscular therapy and help patients to improve motor recovery. This paper describes the development and evaluation of control strategies for a novel lower-limb paediatric rehabilitation robot, based on linear-motor actuator technology and the leg-press exercise modality.

Methods: A functional model was designed and constructed and an overall control strategy was developed to facilitate volitional control of pedal position based on the cognitive task presented to the patient, together with automatic control of pedal forces using force feedback and impedance compensation.

Results: Each independent drive for the left and right legs can produce force up to 288 N at the user's foot. During dynamic testing, the user maintained a variable target position with root-mean-square tracking error (RMSE) of 3.8 ° with pure force control and 2.8 ° with combined force/impedance control, on a range of periodic motion of 20–80 °. With impedance compensation, accuracy of force tracking was also slightly better (RMSE of 9.3 vs. 9.8 N, force/impedance vs. force control only).

Conclusions: The control strategy facilitated accurate volitional control of pedal position and, simultaneously, accurate and robust control of pedal forces. Impedance compensation showed performance benefits. Control accuracy and force magnitude are deemed appropriate for rehabilitation of children with neurological impairments, but, due to current levels required, linear motor technology may not be suitable for applications where higher force is needed. Further work is required to validate the device within the target population of impaired children and to develop appropriate patient-interface software.

1. Introduction

The recovery and maintenance of motor function is one key aim of rehabilitation interventions. Robotic technology is increasingly used in clinical rehabilitation environments to facilitate long training sessions, a large number of movement repetitions, and thereby to improve therapeutic outcomes [1].

The field of rehabilitation robotics is developing rapidly. With faster and more powerful computers, new computational approaches and sophisticated electromechanical components, robots have become an important tool to improve the therapeutic outcomes in rehabilitation [2]. Robots can aid therapists in the implementation of rehabilitation programmes by enabling repetitive, high quality task-specific movements, by increasing the duration and intensity of rehabilitation sessions and by providing a large variety of exercise modalities [3]. Furthermore, robotic systems provide the possibility of recording information about movement parameters (force, position, velocity, etc.) during exercise, which allows the subsequent interpretation and analysis of the therapy performance and progress [4,5].

The current generation of rehabilitation robots differ in terms of mechanical design, actuation technology and control architecture [1,6,7]. They can be categorized with respect to their application focus as assistive or therapeutic devices: assistive robots are used to assist patients in their daily-living activities, whereas therapeutic robots are used to improve various neurophysiological aspects of body function, and they are mainly used in clinical environments [1].

Rehabilitation robots can be further delineated with respect to their mechanical design as either end-effector or exoskeleton sys-

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Notation and abbreviations

F	measured force
F^*	target force
F_{sim}	simulated (nominal) force
F_{imp}	impedance force
θ	pedal angle
θ^*	target angle
i	current
i^*	target current
s	Laplace-transform complex variable
$C_{\text{fb}}(s)$	force feedback controller
$P_o(s)$	plant for force controller
$C_{\text{imp}}(s)$	impedance controller
C_i	current controller
P_i	plant for current controller
IPC	industrial PC

tems. End-Effector robots impose forces on the distal segments of the upper or lower limbs [8], but they cannot directly control individual joints since the contact between the patient and the robot is at limb endpoints. Examples of end-effector rehabilitation robots are the G-EO System [9], MIT-Manus [10], the Gait-Trainer [11], GENTELE/s [12] and Bi-Manu-Track [13]. Exoskeleton-based robots, on the other hand, use external structures attached at several points across the patient's limbs. The joints of the exoskeleton are aligned to those of the human body [14], which allows direct control of the joints [15]. Examples of exoskeleton robots are the Lokomat [16], LOPES [17], ARMin [18], T-WREX [19], Dampace [20] and L-Exos [21].

The dynamic leg-press form of exercise, hitherto applied mainly in the sports context for musculoskeletal conditioning [22,23], has potential as a new modality for neuromuscular rehabilitation applications. Due to the possibility of a compact design, and provision of a safe, semi- or fully-recumbent seated posture, leg-press devices have potential for application particularly in paediatric rehabilitation. Examples of leg-press rehabilitation robots are the Lambda [24], LegoPress [25] and Allegro [26].

The main aim of control strategies for leg-press devices is to provide optimal exercises to promote neuroplasticity and therefore improve motor recovery. For rehabilitation robotics in general, a variety of control strategies have been developed, and several research reviews have been done [27–30]. Rehabilitation control strategies can be categorized in two main groups: (i) trajectory tracking controllers and (ii) assist-as-needed controllers (AAN) [29]. Trajectory tracking controllers are position controllers adapted from those applied in industrial robots. They provide passive repetitive exercise, where the patient's limb is made to follow a predefined trajectory. In advanced versions, known as "adaptive position controllers", the controller allows for deviation from the predefined trajectory based on the motion of the patient [1]. Trajectory tracking controllers are important in the early rehabilitation stages, where passive exercise is needed, but lack the ability to motivate since the active participation of the patient is not of concern at this stage [30]. On the other hand, assist-as-needed controllers adjust the amount of assistance given by the robot based on the patient's real-time contribution and ability. Compared to trajectory tracking controllers, AAN controllers allow more freedom and variability of movement [31] and increase the participation and motivation of the patient [32]. One of the most appropriate AAN approaches which encourages active participation of the patient is impedance control [33,34]. Impedance control strategies allow deviation from the predefined trajectory and do not impose rigid movement. This can regulate the dynamic relationship between the motion of the patient's limb and the force applied by the actuator [35]. Furthermore, impedance control parameters can be adjusted depending on the patient's abilities and needs. Another common AAN approach is a "tunnel controller". This creates a virtual tunnel along the reference trajectory where the patient tries to maintain his limb position. As long as the limb is within the virtual tunnel, the robot will apply no corrective forces. If the limb diverges from the tunnel, the robot will increase the applied force to push the limb back to the desired trajectory [36,37]. The system described in this paper applies impedance control.

The aim of this work was to design, construct and test a novel lower-limb end-effector rehabilitation robot, based on the leg-press exercising approach, with a target population of children with neuromuscular impairments. The system which was developed, as described in this paper, is leg press training device which allows active exercise of the lower limbs. The feet are connected the footplates of two separate pedal mechanisms. The device allows movement of the lower limbs in the sagittal plane, with flexion/extension of the knee joints. The focus in the present report is on the development and evaluation of force and impedance control strategies based on linear-motor actuator technology.

2. Methods

2.1. Device specifications and design

The mechanical design and construction of the prototype device is depicted in Fig. 1 . Since the focus in the present work is on control strategy development, the mechanical design details and specifications are only summarised in brief here.

The prototype device comprises a seat with adjustable backrest and position, footplates attached via a lever mechanism to two independent linear electric motors, and a visual feedback screen positioned at the front. The patient sits on the chair with the backrest adjusted as desired between an almost upright position and an almost fully recumbent position. The feet are placed on footplates attached to separate pedal mechanisms. The maximum range of motion of the footplates is defined by the stroke of the linear motors. To adapt the robot for patients with different body sizes and leg lengths, and to give appropriate joint ranges of motion, the distance between the seat and the footplates is set by moving the chair back or forward. The visual feedback screen at the front provides the patient with motion targets and real-time feedback of key performance variables (e.g. angles and forces) for implementation of specific neuromuscular training and assessment therapies.

The target population for the device is children aged 4–14 years with body mass of up to 50 kg. The device was required to be capable of generating a total continuous force on the footplates corresponding to 1.2 × body mass, i.e. a combined left + right equivalent mass of ~60 kg. The pedals are actuated by two independent drives (left and right legs) each of which is capable of producing a continuous force of 354 N and a peak force of 1024 N. Because of the pedal geometry and available lever arms, the arrangement can generate a continuous force of 288 N at each footplate. This gives a total continuous force magnitude of 288 × 2 =576 N, corresponding to an equivalent body mass of 59 kg, which, according to the above specifications and given the ability of the motors to generate short-term forces of nearly three times the continuous levels, is deemed appropriate for therapy of children with impairments.

The therapy device was required to facilitate rehabilitation exercises for children with neuromuscular impairments. The device can be flexibly programmed for implementation of specific training exercises, and was also designed to meet the following general criteria for neuromuscular and skeletal rehabilitation [38]: