Robotics and Autonomous Systems 105 (2018) 38–46

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

# A three-stage trajectory generation method for robot-assisted bilateral upper limb training with subject-specific adaptation

Qing Miao [a], Andrew McDaid [b], Mingming Zhang [b,c,*], Parham Kebria [d], Hongsheng Li [a]

[a] School of Mechanical and Electrical Engineering, Wuhan University of Technology, Wuhan, China
[b] Department of Mechanical Engineering, the University of Auckland, Auckland, New Zealand
[c] State Key Lab of Digital Manufacturing Equipment & Technology, Huazhong University of Science and Technology, Wuhan, China
[d] Institute for Intelligent Systems Research and Innovations, Deakin University, Australia

## HIGHLIGHTS

- A three-stage trajectory generation method for robotic bilateral arm training.
- The method is able to be subject-specific based on the height of users.
- Seven participants gave positive feedback on this new technique.

## ARTICLE INFO

*Article history:*
Received 23 December 2017
Received in revised form 9 March 2018
Accepted 26 March 2018
Available online 31 March 2018

*Keywords:*
Robot-assisted
Bilateral
Upper limb
Trajectory generation
Workspace
Interference analysis

## ABSTRACT

Robot-assisted bilateral upper limb training typically requires two robotic devices that work cooperatively with a human user. The determination of appropriate movement trajectories is essential to avoid interference of the robotic systems and ensure an appropriate intersecting workspace with user limbs. This paper proposes a new three-stage trajectory generation method for bilateral upper limb training using interference analysis. These three stages include workspace analysis of robots and human hands, trajectory generation within the intersecting workspace, and interference analysis for training safety verification. This trajectory generation method is also implemented with subject-specific adaptation based on anthropometry of an individual. Experiments were conducted on seven healthy subjects with a variety of body sizes. All participants gave positive feedback on the suitability of the predefined training trajectories, and no robot interference was detected. This three-stage method provides guidelines for the standardization of robot-assisted bilateral upper limb training protocols. Future work will focus on proposing an adaptive trajectory generation algorithm with efficacy evaluation on a larger sample of subjects.

## 1. Introduction

Stroke is the second leading cause for acquired disability in adults [1,2]. These survivors are mostly left with disabilities, with the most common being motor impairment of upper limbs [3], which represents difficulties in performing activities of daily living (ADLs). Longitudinal studies indicated that a range from 30% to 66% of stroke survivors do not have full arm function six months post-stroke [4]. However, evidences have suggested that these survivors' upper limb motor skills can be improved by following rehabilitation interventions [5–7]. While a gold standard for treating mild post-stroke upper limb impairment is constraint-induced movement therapy [4], alternative treatments are needed for targeting impaired subjects with varying levels of disability.

Bilateral upper limb training has been widely investigated as a rehabilitation intervention with great potential for clinical applications [8–10]. Activating the primary motor cortex and supplementary motor area of the intact limb can increase the likelihood of voluntary muscle contractions of the impaired limb when symmetrical movements are executed [11]. Studies also indicated that task-oriented repetitive training therapy plays a positive role on the improvement of movement abilities [12,13]. ADLs-based tasks mostly require bilateral cooperation of human limbs.

Robot-assisted upper limb rehabilitation techniques have advanced rapidly in the past few decades [14–17]. With respect to traditional rehabilitation interventions, robotic systems can provide more intensive physical therapy with implementation of

---

[*] Corresponding author.
*E-mail address:* mzha130@aucklanduni.ac.nz (M. Zhang).

https://doi.org/10.1016/j.robot.2018.03.010
0921-8890/© 2018 Published by Elsevier B.V.

various interactive strategies. Stoykov and Corcos [10] found that most bilateral studies involved the use of a device which provides varying levels of assistance to the paretic arm so that it can perform symmetrical or asymmetrical movements more efficiently. The device can be a mechanical one or a computer controlled robot. These robotic systems allow practice with varying levels of assistance including active, passive and active assisted movement modes, and these strategies can be adjusted adaptively on a computer depending on the disability level of an individual.

Robot-assisted bilateral upper limb training aims to stimulate coordinated use of human arms for rehabilitation purpose. A common way is based on master–slave strategy by healthy limbs guiding impaired ones for specific tasks. Li, et al. [18] proposed a master–slave control method on a robot to implement bilateral arm training. The corresponding force provided for the impaired limb is from the healthy limb. In a similar way, Rashedi, et al. [19] implemented the master–slave control on a hand robot to achieve the mirror-image motion pattern. To achieve patient cooperative control, Trlep, et al. [20] developed an adaptive assistance strategy on a bilateral robotic system to adjust the contribution of the unaffected arm for reducing the load on the paretic arm. Trials on four chronic stroke patients showed that participants were all able to apply forces with the paretic arm similar to the forces of the unaffected arm. Trlep, et al. [21] further applied the scaled forces of both arms to produce the control force on the robotic device.

These bilateral robotic devices can be divided into two categories in terms of motion path. One kind is the robots with fixed motion paths, such as the Reha-Slide Duo [22] and a force-induced isokinetic arm robotic trainer [23]. The Reha-Slide Duo consists of a board with two sledges running on parallel tracks. Tung, et al. [23] constructed the bilateral robotic trainer by using two motors and two parallel roller guides. This device was implemented with four different modes, including bilateral passive, bilateral active passive, bilateral reciprocal, and bilateral symmetric upper limb movement. For a specific joint of the human upper limb, Rashedi, et al. [24] developed a hand robotic rehabilitation system to deliver bilateral training of forearm pronation–supination and wrist flexion–extension. In general, these robotic prototypes are characterized with fixed motion paths by setting interference-free movement tracks mechanically.

The other kind of bilateral robots enables continuous planar [25] or spatial [26] workspace for human upper limbs. The training trajectories with these robotic systems need to be programmed on a computer. Miao, et al. [25] implemented bilateral upper limb training by the use of an H-Bot mechanism, where the movement trajectory can be arbitrarily defined inside a plane by programming, not just follow mechanical tracks as those in [22,23]. The motion module of this robotic system consists of two mutually perpendicular linear slide systems and two Maxon motors for actuation. Another example of bilateral upper limb training is the two-arm exoskeleton robot developed by Perry, et al. [26]. This system can provide three-dimensional continuous workspace, with each arm having seven single-axis revolute joints (shoulder abduction–adduction, flexion–extension and internal–external rotation, elbow flexion–extension, and wrist pronation–supination, flexion–extension, and radio-ulnar deviation). While these robotic systems can deliver physical therapy training with customized trajectories, this requires the generation of appropriate movement paths to guarantee safety and efficacy, especially for robotic systems with continuous spacial workspace capacity. However, no studies have been found specifically investigating trajectory generation techniques for robot-assisted bilateral upper limb training.

The determination of appropriate robot-assisted bilateral training trajectories requires the knowledge of many factors, including human arm workspace, robot workspace, and interference analysis of robot links. This paper proposes a new three-stage trajectory generation method, being the first attempt to standardize trajectory generation techniques for robot-assisted bilateral upper limb training. This study uses two universal robots as the robot-assisted bilateral upper limb rehabilitation system.

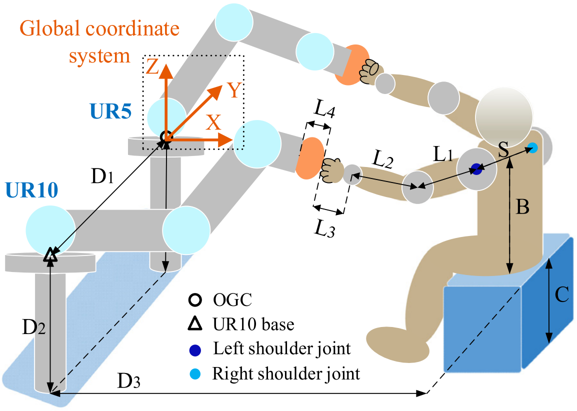

**Fig. 1.** Schematic diagram of the universal robot based bilateral upper limb rehabilitation system (the orange arrowed lines refer to the global coordinate system).

## 2. Methods

This section presents a detailed description of the proposed three-stage trajectory generation method for robot-assisted bilateral upper limb training. It consists of three processes, where Stage 1 conducts workspace analysis of the robotic system and human arms, and works out their intersection, Stage 2 is to determine training trajectories for both human hands, and the trajectory evaluation is finally conducted in Stage 3 based on interference analysis among robot links.

This robotic system consists of two commercial universal robots (UR5 and UR10, Universal Robots A/S) and two customized handles. A schematic diagram of the layout of this robotic system is presented in Fig. 1, where the origin of global coordinate (OGC) is labelled and key dimensions are identified on a subject specific basis. An average set of human segment lengths expressed as a percentage of body height is adapted based on the study by Winter [27]. Considering the height of a subject as $H$, the height of shoulders is $0.818 * H$, the height of waist is $0.530 * H$, and the length of palm is $0.108 * H$. The length of his/her upper body $B = 0.288 * H$, distance between shoulders $S = 0.259 * H$, other parameters $L_1 = 0.186 * H$, $L_2 = 0.146 * H$, $L_3 = 0.054 * H$ (estimated half of the palm length). To make each participant in an appropriate distance of the robot and the chair, $D_3$ is defined as $0.669 * H$. The parameter $D_1 = 1.17$ m, installation height of both robots $D_2 = 1.04$ m, chair height $C = 0.58$ m, and distance of the handle and the robot end effector $L_4 = 0.074$ m.

### 2.1. Workspace analysis

The human upper limb is often considered as a model with seven degrees of freedoms (DOFs), three DOFs for shoulder, two DOFs for elbow and two DOFs for wrist [28]. In this study, it is defined based on a healthy subject that the range of motion (ROM) of the shoulder in flexion is 180°, and ROM of shoulder in extension is 80°. The human shoulder can attain up to 180° of abduction and 50° of adduction. Internal rotation of the shoulder is 90°, and 90° for external rotation. Elbow flexion and extension are 145° and 100°, respectively. The elbow pronation is 90° and supination is 90°. Wrist flexion is 90° and extension is 70°. Wrist adduction is 40° and abduction is 15°.