Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

A planar 3DOF robotic exoskeleton for rehabilitation and assessment

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Abstract— **A new robotic exoskeleton for the upper-limb has been designed and constructed. Its primary purpose is to act as a proof-of-concept prototype for a more sophisticated rehabilitation and assessment device that is currently in development. Simultaneously, it is intended to extend the capabilities of an existing planar exoskeleton device. The robot operates in the horizontal plane and provides independent control of a user's shoulder, elbow and wrist joints using a cable-driven actuation system. The novel component of the design is a curved track and carriage which allows the mechanism that drives the shoulder joint to be located away from the user, underneath their arm. This paper describes the design of the robot, and provides an initial indication of its performance.**

I. INTRODUCTION

As the Canadian population ages, stroke is quickly becoming a leading cause of physical disability in adults, with an estimated 50,000 new occurrences every year [1]. Stroke survivors are typically left with motor impairments although it is often possible to recover some motor function through intensive rehabilitation. It is generally agreed that practicing functional multi-joint movements with the impaired limb is an important part of motor recovery [2]. As such, current therapeutic techniques focus on training with repetitive, frequent functional movements [3].

Providing each stroke patient with the attention they need is a challenge. Each patient requires extensive one-on-one attention, and therapy programs are physically exhausting for the therapist. The possibility of using robotic devices as a more efficient means of providing therapy has been at the forefront of recent stroke rehabilitation research [4], [5]. Robots not only have the ability to provide repetitive functional movement training, but also can provide sensitive and objective quantitative assessments of movement. This technology also makes it possible for a single therapist to supervise multiple patients simultaneously.

Several current upper-limb robotic devices can mimic motion at the wrist, the elbow and/or the glenohumeral joint of the should complex [6]–[10], but none have the ability to reproduce motion at the shoulder girdle. Without full shoulder girdle motion, robots are limited in their ability to provide truly functional movement training. A new device called MEDARM is in development, aiming to overcome this obstacle by providing independent control of all five major degrees of freedom (DOF) at the shoulder complex [11].

MEDARM's design is based on a unique cable-driven curved track mechanism that requires testing at the prototype level before continuing the development process. It was decided that these new ideas should be evaluated using a simpler robot, so that unanticipated practical issues could be more easily addressed. In addition to testing the design concepts of MEDARM, it was decided to also use this simpler robot as a prototype for revisions to the KINARM system which is used in this research lab to assess and manipulate the mechanics of multi-joint motion [12]. KINARM is a robotic exoskeleton that attaches to the upper-limb, allowing movements of the shoulder and elbow in the horizontal plane (2DOF). The system offers high backdriveability, a lightweight structure and low friction. Its primary use is in studying motor control, but it is also showing promise as an assessment tool for patients with motor disabilities including stroke [13], [14].

KINARM's capabilities can be extended or improved in several ways. It currently provides 2DOF (shoulder/elbow) in the horizontal plane, but the current design cannot be easily adapted to provide a third DOF at the wrist. In addition, the only structural support for the mechanism is vertically aligned with the shoulder joint axis and is located beside the user's head. While this may not be a problem for many users, others may find it confining, particularly for bilateral systems. Vertical compliance (out of the plane) is also an issue with this structure. A cable-driven curved track system based on MEDARM's design provides a feasible solution for these concerns. Thus, a new device called Planar MEDARM has been designed to act as both a prototype for MEDARM and a design change for KINARM. This paper describes the design of Planar MEDARM and its initial performance.

II. DESIGN OBJECTIVES

The goal was to build a prototype which used the novel design features of MEDARM to extend the capabilities of KINARM. The main objectives are summarized as follows:

- Planar 3DOF motion: 1 shoulder, 1 elbow, and 1 wrist.
- Shoulder joint motion is to be provided by a curved track system similar to MEDARM.
- All parts of the system should be placed away from the user's head, either behind the user or under their arm.
- Entirely cable-driven.
- Backdriveable, lightweight, and low friction.

The planar nature of the device simplifies implementation, requiring fewer motors and no gravity compensation. However, this planar prototype shares many of the design

Manuscript received April 1, 2007. This work was supported by the Canadian Institutes of Health Research (CIHR), and the Natural Sciences and Engineering Research Council of Canada (NSERC).

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objectives outlined for MEDARM [15] as it still includes kinematic redundancy and similar human-robot interfacing.

III. Design Specifications

The planar MEDARM (Fig. 1) is a 3DOF exoskeleton robot that provides motion at the shoulder, elbow and wrist in the horizontal plane. The entire mechanism is located underneath the user's arm, and because all joints are actuated by a cable-drive system, all motors are located behind the user. All three joints axes are parallel, and the distances between the axes are fully adjustable to accommodate users of different size.

A. Joint Layout

A schematic of the Planar MEDARM mechanism is shown in Fig. 2a. The hinged linkage drives a carriage along a curved track such that its centre of rotation is aligned with the user's shoulder joint axis. One end of the linkage is attached to the elbow joint (which in turn is attached to the carriage), and the other end (shoulder driving joint) is fixed at a location offset from the shoulder joint axis. The resulting mechanism is a virtual 4-bar linkage in that it operates like a 4-bar linkage without any physical structures near the shoulder joint axis. The elbow and wrist DOF are simple rotary joints, aligned directly with the user's elbow and wrist.

Planar MEDARM's structure is similar to the KINARM (Fig. 2b) in that both can be described as a 4-bar linkage. The key difference is that the Planar MEDARM does not require any physical structures on the shoulder joint axis. The advantage is that the robot can be placed entirely beneath the user's arm. An additional benefit of this design is reduced vertical compliance because the weight of the arm will be directly supported by the carriage near the elbow joint axis.

The hinged linkage driving the carriage also serves to guide the cables along the mechanism. A second linkage guides the cables between elbow and wrist joints. These linkages ensure that the cables maintain tension when the length of the mechanism is adjusted. All links are custom machined aluminum to keep the mass and inertial properties

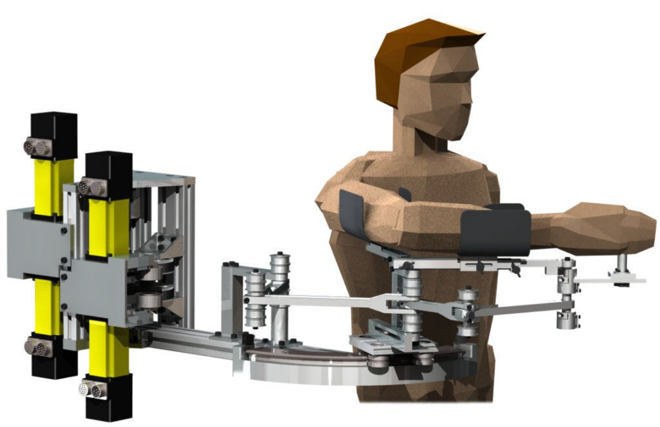

Fig. 1. A CAD drawing of the Planar MEDARM. The 3DOF mechanism is entirely underneath the user's arm. The cable-drive system allows the motors to be located behind the user (cables not shown).

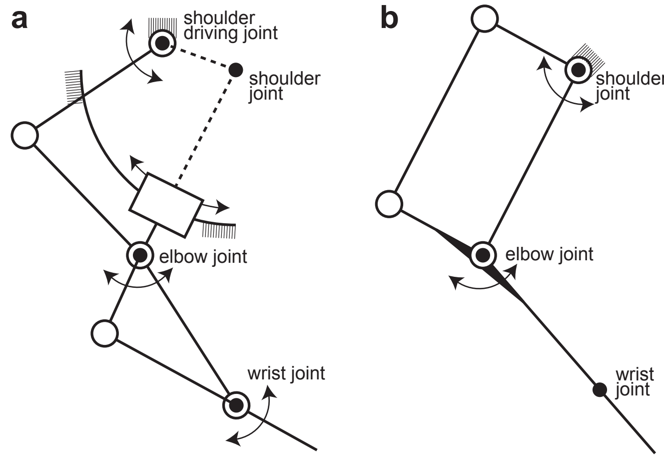

Fig. 2. Top view schematics of (**a**) Planar MEDARM and (**b**) KINARM. KINARM is supported only at the shoulder joint, while Planar MEDARM is supported and guided by its curved track, creating a virtual 4-bar linkage (see dashed lines in (**a**). The other major difference is that Planar MEDARM offers a third DOF at the wrist, while KINARM does not.

low. Each joint has mechanical joint limits to ensure that the robot does not extend the user's arm beyond safe limits.

B. Cable-Drive System

All three DOF are actuated by an open-ended cable-drive system that is similar to the one proposed for MEDARM (Fig. 3). Open-ended cable systems can apply force in one direction only, so it is necessary to have at least one more cable than DOF to achieve motion in both rotational directions at each joint [16]. Thus four cables driven by electric motors are required for the Planar MEDARM to achieve full motion capability.

As a consequence of the imbalance between the number of cables and DOF in cable-drive systems, additional transformations are required to relate motion of the motors to motion at the joints. First of all, the cables span multiple joints, so motion and torque about a single joint is shared among the cables. Also, the position of the hinged linkage driving the carriage affects the length of the cables, and therefore must be included in the calculations. Overall, cable displacement, s, and joint angle, θ, can be related using (1). Likewise, cable force, ξ, and joint torque, τ, are related using (2). These relationships are illustrated in Fig. 3b.

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix} = \begin{bmatrix} -r_{sd} & r_e & -r_w & -1 \\ r_{sd} & -r_e & -r_w & 1 \\ -r_{sd} & -r_e & r_w & 1 \\ r_{sd} & r_e & r_w & -1 \end{bmatrix} \begin{bmatrix} \theta_{sd} \\ \theta_e \\ \theta_w \\ \Theta_{hl} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \tau_{sd} \\ \tau_e \\ \tau_w \end{bmatrix} = \begin{bmatrix} -r_{sd} & r_{sd} & -r_{sd} & r_{sd} \\ r_e & -r_e & -r_e & r_e \\ -r_w & -r_w & r_w & r_w \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix} \quad (2)$$

Note the use of the subscript 'sd', which refers to the shoulder driving joint, not the shoulder joint angle itself

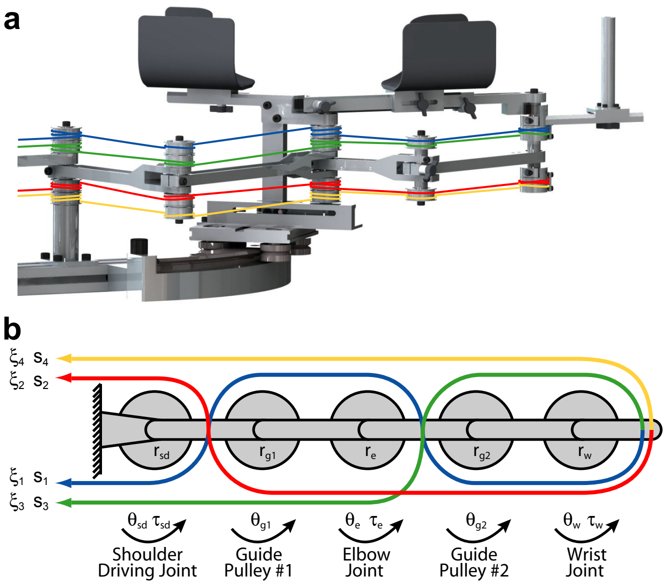

Fig. 3. (**a**) A CAD drawing showing the cable routing scheme used for the Planar MEDARM. (**b**) A simplified planar schematic representation of the optimal cable routing structure. Each of the four cables is denoted by a different colour. Symbols s, ξ, r, τ and θ represent cable displacement, cable force, pulley radius, joint torque and joint angle respectively.

(θ_s) which can be calculated using standard 4-bar linkage relations. The contribution of the hinged linkage motion to the cable displacement is denoted by Θ_{hl}.

The choice of cable routing scheme has a significant effect on the performance of the device. There are five unique cable routing schemes for a 3DOF system [17]. The schemes were be analyzed to find the choice which has minimal antagonism between cables and hence the most even distribution of forces across the cables, and also has the lowest peak forces. Fig. 3 illustrates the optimal routing scheme for this robot.

C. User Interface and Alignment

The user alignment and attachment design is similar to KINARM. Both the elbow and wrist joint locations are adjustable to accommodate users with different upper arm and forearm lengths. The elbow adjustment is made by a sliding the mechanism relative to the carriage. A single quick-release clamp is used to clamp the mechanism in place. The forearm linkage is telescopic and is clamped by thumbscrews.

The user is secured to the mechanism at the upper arm and forearm using molded fiberglass arm cuffs which can be adjusted along the linkages. Currently, the subject grasps a handle. All cuffs and the handle are adjusted with a single thumbscrew clamp. Unlike the MEDARM, there is no motion out of the plane, so there is no need to adjust the height of the cuffs. In addition to attaching the user's arm to the exoskeleton, it is necessary to align the glenohumeral joint centre with the robot. Initially, this will be achieved simply through adjustment of the chair position.

IV. Dynamic Model and Simulation

A dynamic model was created for the Planar MEDARM in MATLAB based on the robot toolbox [18]. Simulations were used to select appropriate motors and cables, and to assist with structural design.

The model is defined as a standard rigid-body manipulator with negligible cable dynamics. Dynamic parameters of the exoskeleton are estimates from CAD drawings, and upper limb parameters were calculated from anthropometric data tables based on user height and weight [19]. The model first calculates the joint torques required to achieve a given trajectory. The cable forces required to generate these joint torques are then calculated using the torque resolver technique, which includes a pretension force to prevent the cables from becoming slack [17]. All forces and non-axial moments at each joint are calculated to evaluate joint strength.

Simulations were performed for various reaching movements with a peak end-point velocity of 1.0 m/s. Movements included single-joint motion through each joint's full range, and a variety of multi-joint reaching movements. In all cases, anthropometric limb measurements were chosen to meet the maximum design requirements. Motors, gear ratios, cables and joint bearings were selected based on the results of these simulations. The overall torque capability of each joint of the exoskeleton with a gear ratio of 3 for each motors is ± 9 Nm (static) and ± 15 Nm (dynamic). Each motor incorporates an electric brake to ensure that the cables remain in tension when the power is turned off. Each motor has a built-in high resolution encoder capable of measuring joint angle in increments of 0.006°. In addition, secondary encoders will be mounted directly to each of the three joints.

V. Performance

The Planar MEDARM has been fully assembled (Fig. 4), and is currently undergoing performance evaluation. Initial tests have confirmed that joint angles are correctly calculated using cable length changes. The robot can be moved passively while pretension is applied to all cables, and torques can be applied independently and across multiple joints.

The first tests compare the in-plane and vertical stiffness of the Planar MEDARM with the KINARM. Stiffness has a significant impact on the overall performance of a robot.

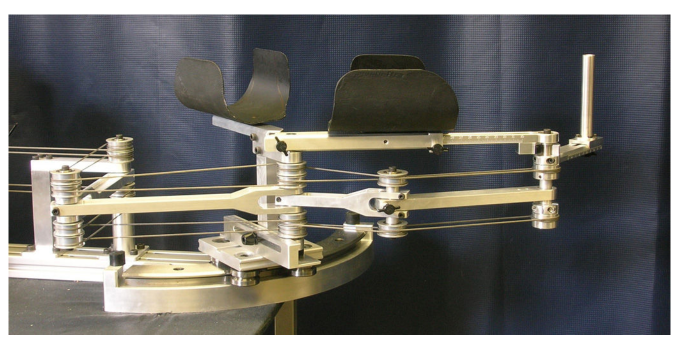

Fig. 4. A photo of the fully constructed Planar MEDARM prototype. Motor systems are off of the picture on the left side.

TABLE I

STIFFNESS OF THE PLANAR MEDARM AND THE KINARM.

Robot	In-Plane Joint Stiffness (Nm/rad)		Vertical Stiffness (N/mm)
	Shoulder	Elbow	
KINARM	625	300	7.6
Planar MEDARM	50^{+}, 30^{-}	20	21.5

With low stiffness, tight position control is not possible, and it is difficult to accurately measure true joint angles without secondary encoders on the joints. Sources of compliance include elasticity of cables and belts, and bending of shafts and linkages. To make the two robots directly comparable, Planar MEDARM's wrist joint was removed and the cable routing scheme was adapted for shoulder and elbow motion. In-plane stiffness of the shoulder and elbow were measured with respect to the endpoint by commanding each joint to move against a rigid surface while reading the change in position noted by the motor encoders. Vertical stiffness was measured by placing known masses at the end point and observing the resulting vertical displacement of the linkages. Results are shown in Table I.

As shown in Table I, the KINARM is an order of magnitude stiffer than Planar MEDARM for in-plane motion. Calculations indicate that the majority of compliance in the Planar MEDARM system arises from cable stretch. This is expected because the prototype uses small, off-the-shelf cables and pulleys to reduce costs. The stiffness of a cable system depends on the square of both the cable and pulley diameters, so for the Planar MEDARM, the stiffness can be increased by a factor of 10 to 12 (close to KINARM stiffness) simply by doubling both of these quantities. Choosing a stiffer cable and reducing its total length would increase the stiffness even further. Note that for the Planar MEDARM, the stiffness of the shoulder is different for positive and negative rotations due to the distribution of the cables.

As expected, the vertical stiffness of the Planar MEDARM is greater than the KINARM. This is due to the rigid support provided by the curved track system. The compliance that exists in the Planar MEDARM is primarily a result of the elbow joint shaft bending. A further increase in stiffness would be easily achieved by stiffening this joint.

VI. CONCLUSIONS AND FUTURE WORK

A prototype upper-limb exoskeleton robot has been designed and constructed. Planar MEDARM is designed as a proof-of-concept prototype for a novel cable-driven curved track mechanism, and as a revision for KINARM. Initial tests of performance indicate that the robot is functioning as expected. Vertical stiffness is significantly higher than the KINARM. In-plane stiffness of the current prototype is an order of magnitude less than KINARM, but simple modifications will increase stiffness to comparable levels.

The next step will be to evaluate motion performance. Encoders will be mounted to the joints to provide accurate joint angle measurements and to enhance position control performance. Friction in the system will also be examined. An alternate cable routing scheme that requires only two cables to drive the wrist will be implemented to more easily observe the contribution of pulley bearing friction to the total friction.

The prototype has already proved an invaluable insight into the development of the full MEDARM robot. All experience will be transferred to the MEDARM design.

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