

DESIGN OF BIO-EXOSKELETON FOR ELBOW REHABILITATION

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ABSTRACT

In this study, a methodology for designing a task-based exoskeleton which can recreate the end-effector trajectory of a given limb during a rehabilitation task/movement is presented. The exoskeleton provides an option to replace traditional joint-based exoskeleton joints, which often have alignment issues with the biological joint. The proper fit of the exoskeleton to the user and task are research topics to reduce pain or joint injuries as well as for the execution of the task. The proposed task-based synthesis method was successfully applied to generate the 3D motions of the elbow flexion and extensions using a one degree of freedom (DOF), spatial four-bar mechanism. The elbow joint is analyzed through motion capture system to develop the bio-exoskeleton. The resulted exoskeleton does not need to align with the corresponding limb joint to generate the desired anatomical motion.

INTRODUCTION

An increase in research interest has been shown in assistive robotics and exoskeletons due to their capabilities in providing

assistance and supporting physical therapy procedures [1]. The demand of such devices has increased partly due to the increasing number of people in the aging community with motor impairments and paralysis due to stroke [2]. Studies reveal that the motor impairment of the arm is a common consequence after suffering a stroke [3]. Analyzing the motion of the elbow joint can be helpful for arm rehabilitation [4]. The simplification of the elbow joint into a single or double revolute joint has been a subject of interest, but the need of a proper analysis of this joint is still needed to address its proper motion. Many exoskeletons have been simplified and designed to mimic and align the human joints (e.g. a hinge joint for the elbow) [5]. However, researches have shown that the simplified model of human joints could cause a different result from the natural human joint kinematics [6]. This misalignment of joint motion may induce unwanted external forces that could cause abnormal wear and premature loosening of the muscles [7]. Evidence addressing the magnitude of the forces due to misalignment can be found in the literature. Schiele [8] study the misalignment of traditional joint-to-joint exoskeleton. In this work he uses the EXARM exoskeleton, which is an ergonomic device. This device has passive joint that minimizes parasite forces that appear on the human joint due

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to misalignment. Two set of tests were performed, in the first one, the passive joints were locked, which mimics the behavior of a non-ergonomic traditional exoskeleton, and on the other test, they were unlocked. The results clearly show that for the first case, the reaction forces at the joint ranged from -13.5N to 10N, whereas the second case the reaction forces were minimized, and they ranged from -6 to 2.6N. Also, Desplenter et al [9] in their study compared available models in OpenSim, which model the elbow joint as a 1 degree of freedom revolute joint with EMG data from a human subject. Seven different models were used, the experimental results show that torque errors ranged between 1.67–2.19 Nm. The errors shown in both studies could cause excess strain on soft tissues of the human body, causing discomfort and pain, especially to those with sensitive soft tissues and those in rehabilitation due to injuries.

An ideal exoskeleton must generate natural motion within the workspace of the human limb without causing any motion changes. However, researches have shown that the anatomical joint axis and biomechanics are constantly changing due to the coordination of ligaments and muscles during the motion or flexion/extension of the joint [10]. Thus, exoskeletons that are not in-line with the human anatomical joint parameters could also cause discomfort to the user and affect the overall intervention procedure.

To reduce the effect of joint alignment, some researchers have proposed an end-effector-based robotic devices that attaches to the targeted limb [11]. This approach provides a free range of motion and rotation at the joint and heavily depend on the study of anatomical joint motion data. Thus, the capturing and representation of the anatomical motions are very important for the realization of the final device. In this study, identification of limb trajectory through motion capture is performed to analyse variability of the joint axes and target limb trajectory, and an advanced mechanism synthesis is followed to obtain a bio-exoskeleton.

METHODOLOGY

The methodology involves collecting human motion kinematic data, and identifying trajectory representation capable of reproducing the desired motions. The desired task has been traditionally specified as a set of finite precision positions that are generated by the targeted limb. Polhemus Micro Sensors 1.8 and a LIBERTY tracking system is used to track the hand motion in real time. The experimental setup is shown in fig. 1(a). A human arm is placed on a table with the motion tracking system for the analysis of motion and rotation of areas of interest, especially the elbow joint. Sensors are also placed on the forearm and the upper arm for further points of references. The subjects were tasked to perform flexion and extension movements. The motion ranges from the upperarm to the surface of the table. The upper arm is constrained to decouple the upper body motion ef-

flect. Adjustable mechanisms are utilized for the setup to address subject height variability, Fig. 1(b) shows the arm holder used in the experiment. Data was collected using PiMgr software at a

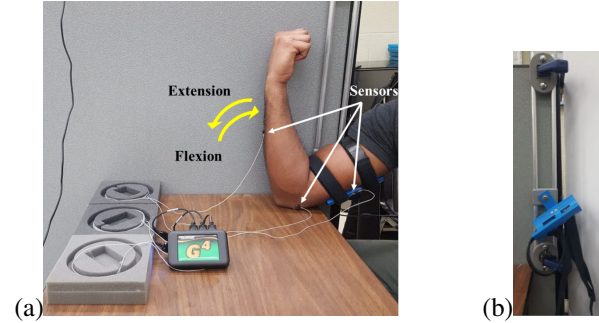


FIGURE 1: (a) Experimental setup, and (b) Arm holder

rate of 2800 frames/sec while subjects performed the elbow flexion and extension. The data from the sensor at the forearm of the subject is used as the base for the desired trajectory and also for the attachment of the end-effector. The data from the sensor for the elbow flexion-extension is shown in fig. 2 (a). From this trajectory, 12 equally spaced points were selected to be used in the mechanism synthesis (fig. 2 (b)).

MECHANISM SYNTHESIS

A task-based design methodology is adopted to yield an articulated system that can reproduce the desired limb trajectory from the motion capture. Due to their rigidity and higher payload, a lower degree-of-freedom parallel mechanisms have been considered. The overall synthesis procedure is shown in fig. 3.

In this study, a one-DOF, RRRR mechanism also known as Bennett's linkage is selected

Following the labels of fig. 4, the lengths of the links and the twist angles of the revolute joints of opposite sides must be equal, i.e $a_{12} = a_{34} = \alpha$, $a_{23} = a_{41} = \beta$ and $\alpha_{12} = \alpha_{34} = a$, $\alpha_{23} = \alpha_{41} = b$, respectively in order to have a 1-DOF motion. Also, the link lengths and twist angle must satisfy $\frac{\sin \alpha}{\sin \beta} = \frac{a}{b}$, and the joints offset must be zero. If all the constraints are met, the mechanism will have one DOF [12].

The Bennett's linkage is a parallel robot with two RR-serial chains joined at the end-effector. The kinematics of the serial chain of the mechanism will be formulated using Clifford algebra exponentials. This approach defines the axis of each joint using Plücker coordinates $S_i = s_i + \epsilon s_0^i$ for $i = 1, 2, 3, \dots, n$, where s_i is a unit vector describing the direction of the axis, s_0^i is the moment of the line ($c_i \times s_i$) with respect to the reference frame and $\epsilon^2 = 0$. The exponentials of the Clifford subalgebra of the projective space can express spatial displacement, in this space the unit

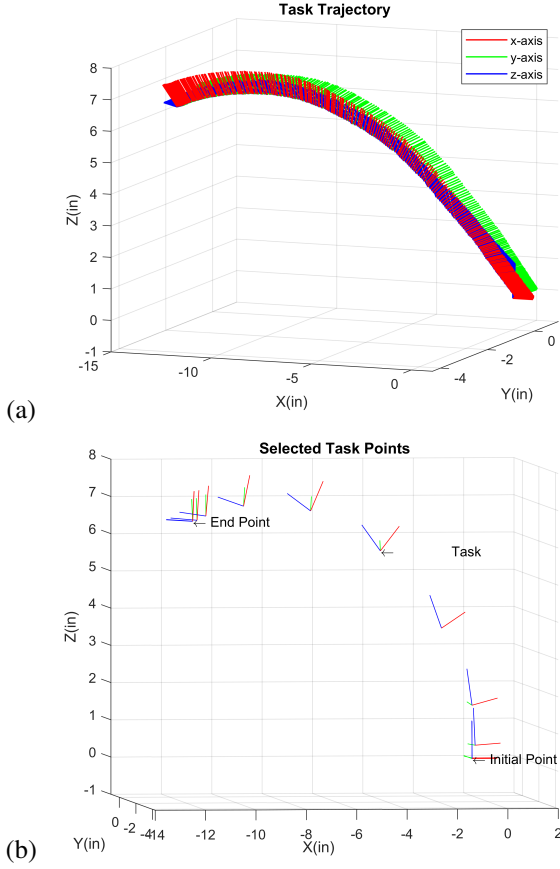


FIGURE 2: Motion captured data (a) the whole trajectory poses, and (b) selected poses for synthesis

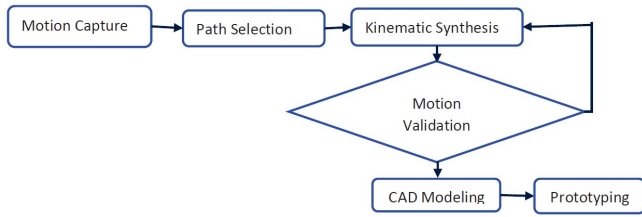


FIGURE 3: Design Methodology

elements are known as dual quaternions. The forward kinematics is expressed as $\hat{Q}(\theta) = e^{\frac{\hat{\theta}_1}{2}S_1}e^{\frac{\hat{\theta}_2}{2}S_2}e^{\frac{\hat{\theta}_3}{2}S_3}\dots e^{\frac{\hat{\theta}_n}{2}S_n}e^{\frac{\hat{\theta}_0}{2}S_0}$ where $\hat{\theta}_i$ depends on the joint parameters. This formulation adds two constraints for each revolute joint, and one constraint for each prismatic joint. Once the selected mechanism topology forward kinematics is formulated, the task positions need to be expressed in a similar fashion. Consider $[P_1]$, the reference position in the desired trajectory of m number of points, and the relative displacements are defined as $[P_j][P_1^{-1}] = [P_{1j}], j = 2, \dots, m$. Then,

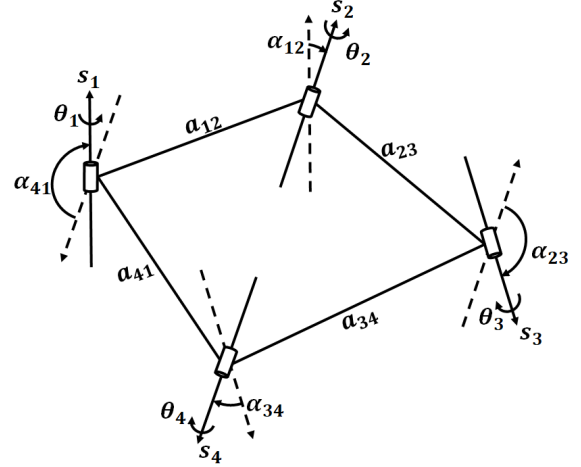


FIGURE 4: Spatial four bar linkage Diagram.

the mathematical equations are formulated to find the joint axes of the robotic exoskeleton. The $(m-1)$ relative displacements of the serial chain are equated as

$$[\hat{P}_{1j}] = e^{\frac{\Delta\hat{\theta}_{1j}}{2}S_1}e^{\frac{\Delta\hat{\theta}_{2j}}{2}S_2}\dots e^{\frac{\Delta\hat{\theta}_{nj}}{2}S_n}, j = 2, \dots, m.$$

The unknowns are the n joint axes $s_i, i = 1, \dots, n$, and the $n(m-1)$ pairs of joint parameters $\Delta\hat{\theta}_{ij}$. With this approach, the joints of the exoskeleton are solved based on the task; there is no need of aligning the exoskeleton joint to the human limb joints.

For the RRRR linkage, each chain (RR) is analyzed separately, then set the position and orientation of the end-effector to reach each point of the desired task. As it is shown in figure 5, each chain, i.e RR, provided solutions that follow the desired trajectory as close as possible while meeting the established constraints. However, when the two chains are connected to form the complete exoskeleton/mechanism (RRRR), the motion may suffer from an over constrained situation and may not move. In such situation, a visual representation of the workspace of each chain (RR-linkage) and intersection of the two are important to differentiate the best and unconstrained solution. In other words, the desired task trajectory must lie on a continuous region of the workspace of the connected chains.

The trajectory generated by the two kinematic chains are plotted as shown in fig.5, where the axis-frames colored red, green and blue correspond to points selected from the task, and the ones colored as black, yellow, and brown represent the spatial points from the kinematic chains. Due to the small error between the spatial points, it is difficult to notice any difference.

Two different solutions were selected and shown in Fig. 6– left shows a feasible solution as the desired task (yellow) lies on the single intersection of the two chains, but Fig. 6– right shows one where the solution lies on two different continuous regions

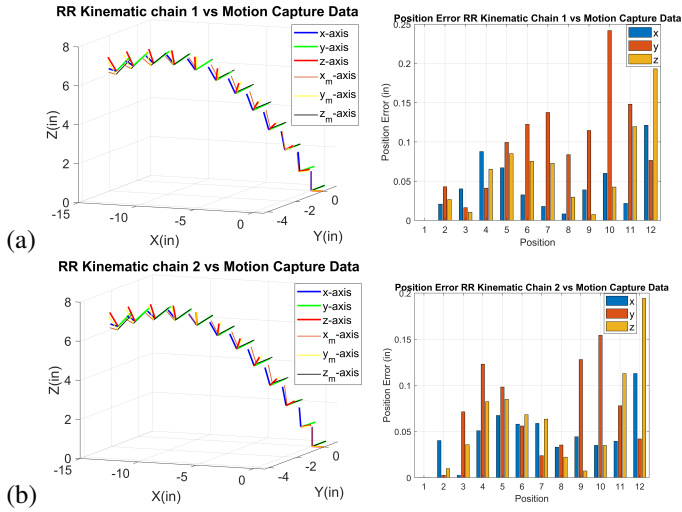


FIGURE 5: (a) Comparison between Selected Task Points vs Kinematic chain 1, and (b) Comparison between Selected Task Points vs Kinematic chain 2.

of the joined workspace of the RRRR linkage. Fig. 6-b shows the desired elbow flexion-extension trajectory on the common workspaces of the two chains, indicating the desired workspace can be traced by the mechanism with no circuit defect.

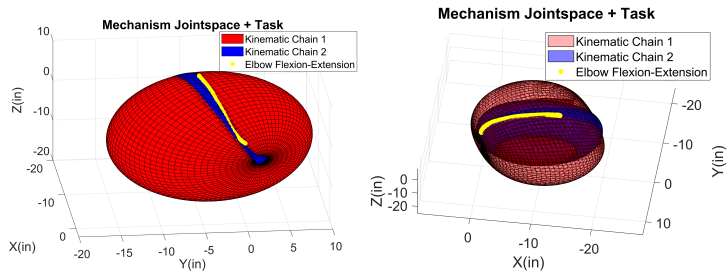


FIGURE 6: Flexion-Extension trajectory and intersection of two Joint spaces of RR-Chains showing the mechanism does not need to disassemble to follow the trajectory.

RESULTS AND DISCUSSIONS

As a demonstration, a mechanism has been designed and modeled in the CAD based on the parameters found through the proposed mechanism synthesis approach. The CAD model and the trajectory generated by it is illustrated in fig. 7. The blue link represent the fixed frame, and the end-effector is shown using the green link. The detail design and the placement of the mech-

TABLE 1: Bennett Linkage Parameters from Synthesis

Parameters	Values	Parameters	Values
a_{12}	91.76mm	α_{23}	63.32°
a_{23}	84.71mm	α_{34}	75.45°
a_{34}	91.76mm	α_{41}	63.32°
a_{41}	84.71mm	α_{41}	63.32°
α_{12}	75.45°	$\frac{a_1^2}{a_2^3}$	1.0833
$\frac{\sin \alpha_{12}}{\sin \alpha_{23}}$	1.0833		

anism on the arm is also shown in fig.8. The precise positioning of the designed system is easier as it lies on a larger upper and forearm surface areas as opposed to aligning to the biological joint axes of the elbow.

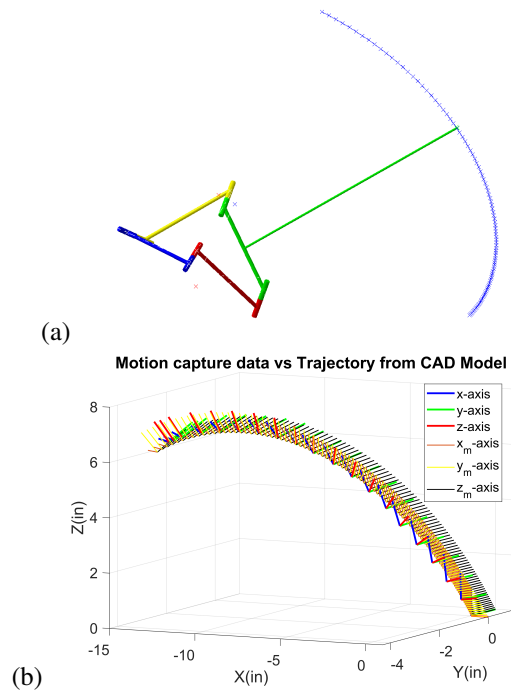


FIGURE 7: (a) CAD model of the proposed mechanism, and (b) Trajectories from motion capture system vs the CAD model.

CONCLUSIONS

A spatial kinematic synthesis is performed to reproduce the trajectory of the elbow flexion-extension motion using a sin-

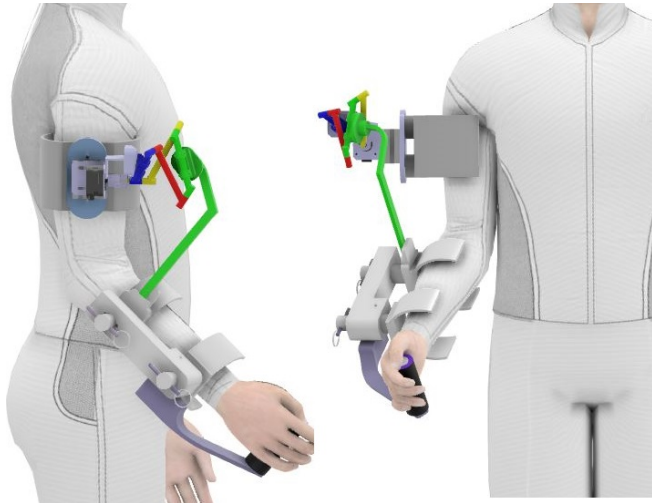


FIGURE 8: CAD model of the proposed mechanism, as it is placed on the arm.

gle DOF spacial mechanics and without mimicking the human anatomy. The desired trajectory of the elbow was captured by a motion capture system. The error between the task and the mechanism trajectory obtained by kinematic synthesis showed an error of 0.05474, 0.01132, and 0.0804 inches in the X, Y, and Z direction, respectively. In the same way, the highest RMSE of the rotation matrix components is 0.02894.

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