Real-Time Estimation of Glenohumeral Joint Rotation Center With Cable-Driven Arm Exoskeleton (CAREX)—A Cable-Based Arm Exoskeleton

Ying Mao²

GE Global Research,
1 Research Circle,
Niskayuna, NY 12309
e-mail: yingmao@ge.com

Xin Jin

Department of Mechanical Engineering,
Columbia University,
New York, NY 10027
e-mail: xj2146@columbia.edu

Sunil K. Agrawal¹

Professor
Department of Mechanical Engineering,
Columbia University,
New York, NY 10027
e-mail: Sunil.Agrawal@columbia.edu

In the past few years, the authors have proposed several prototypes of a Cable-driven upper ARM EXoskeleton (CAREX) for arm rehabilitation. One of the assumptions of CAREX was that the glenohumeral joint rotation center (GH-c) remains stationary in the inertial frame during motion, which leads to inaccuracy in the kinematic model and may hamper training performance. In this paper, we propose a novel approach to estimate GH-c using measurements of shoulder joint angles and cable lengths. This helps in locating the GH-c center appropriately within the kinematic model. As a result, more accurate kinematic model can be used to improve the training of human users. An estimation algorithm is presented to compute the GH-c in real-time. The algorithm was implemented on the latest prototype of CAREX. Simulations and preliminary experimental results are presented to validate the proposed GH-c estimation method. [DOI: 10.1115/1.4025926]

1 Introduction

In the last two decades, robot-aided upper extremity training has been studied extensively to improve the recovery of neuromuscular functions of stroke patients [1,2]. Current robotic rehabilitation devices can be classified in two categories. These are (i) end-effector devices which interact with the arm only at the handle [3,4], and (ii) exoskeletal devices with rigid links in parallel with the human limb segments [5,6].

Compared to end-effector devices, exoskeletons offer independent joint torque control, which enables therapy targeting specific joint or muscle group and precise repetitions of joint movement. However, an important limitation of an exoskeleton is that the mechanical joint axes need to be precisely aligned with

the arm joint axes in order for the exoskeleton to function properly. This is particularly difficult for the upper extremity due to complexity of translation of glenohumeral joint. Poor joint axes alignments induce large reaction forces and moments at the joints and may further cause skin sore and soft tissue damage [7]. Therefore, this issue needs to be properly addressed to ensure the safety and ergonomics of an arm exoskeleton. Some designs have attempted to accommodate the glenohumeral joint translation by adding extra active or passive degrees-of-freedom [5,8,9]. However, this complicates the mechanical design and increases the moving inertia of the arm.

In the last few years, Agrawal et al. presented several prototypes of CAREX [10–14]. The key features that differentiate CAREX from existing designs are: (i) It does not have traditional links and joints, hence does not require mechanical joint axes alignments and segment lengths adjustments. (ii) It does not induce reaction forces or moments due to joint axes misalignment. (iii) Cables are routed from proximal to distal arm segments and serve as structural members of the exoskeleton. (iv) It is the first exoskeleton of its kind that can generate forces in all direction at the end-effector while keeping cables in tension. (v) It is nearly an order of magnitude lighter than conventional exoskeletons [15]. One of the assumptions of CAREX in the past studies was that the GH-c remains stationary during training. This is not completely valid due to complex articulations within the shoulder [16]. In the absence of traditional links and joints, CAREX does not induce reaction forces or moments due to the mismatch of GH-c. However, this mismatch leads to inaccuracy in the kinematic model, hence may deteriorate the training performance of CAREX. In this paper, we propose a novel approach to estimate GH-c during training. An analytical method that computes the location of GH-c using cable lengths and glenohumeral joint angles is presented. A computationally efficient algorithm is proposed to estimate GH-c in real-time. Simulations and preliminary experiments are performed to validate the proposed GH-c estimation method.

2 Exoskeleton Design and Kinematics

A sketch of a subject wearing CAREX is shown in Fig. 1. The exoskeleton consists of three cuffs—the shoulder cuff, the upper arm cuff, and the forearm cuff. The shoulder cuff is fixed on a metal frame that supports the motors. The upper arm cuff and the forearm cuff are attached to an arm orthosis, whose upper arm segment and forearm segment are connected by a hinge. The size of the orthosis can be adjusted to firmly strap it on the arm of different subjects. An orientation sensor is attached to the upper arm which measures the glenohumeral joint angles. A rotary encoder is installed at the hinge to measure the elbow angle. The total weight of the exoskeleton, including the orthosis, is only 1.32 kg. This is an order of magnitude less than exoskeletons with traditional links and joints [5,17,18].

The coordinate frames of CAREX are shown in Fig. 1. The exoskeleton controls four degrees-of-freedom in the human shoulder and elbow using seven cables. Within the mathematical model of the human arm, joints 1–3 represent the translation of the GH-c in the inertial frame. These degrees-of-freedom are not controlled. Joints 4–6 represent the glenohumeral joint, i.e., flexion/extension, adduction/abduction, internal/external rotation of the shoulder. Joint 7 is the elbow flexion/extension. Details on exoskeleton design, cable management, workspace optimization, and control can be found in Ref. [15].

3 Estimation of Glenohumeral Joint Rotation Center

CAREX is equipped with an orientation sensor and a rotary encoder. These measure the glenohumeral joint angles and elbow joint angle. In order to have complete information of the exoskeleton kinematics, the location of GH-c, i.e., the generalized coordinates q_1, q_2, q_3 , must be estimated in order to ensure accurate kinematic model for control of the training forces. In this section,

¹Corresponding author.

²Ying Mao is currently affiliated with GE Global Research. All work presented in this paper was completed prior to joining GE at University of Delaware.

Contributed by the Mechanisms and Robotics Committee of ASME for publication in the JOURNAL OF MECHANISMS AND ROBOTICS. Manuscript received February 21, 2012; final manuscript received September 26, 2013; published online December 27, 2013. Assoc. Editor: Kazem Kazerounian.

Fig. 1 Left: Coordinate frames of CAREX. Right: Close-up view of a subject wearing CAREX. (A: Shoulder cuff. B: Upper arm cuff. C: Forearm cuff. D: Extension bar. E: Orientation sensor. F: Rotary encoder. G: Load cells.)

we present an analytical method to estimate the location of GH-c using cable lengths and shoulder angles q_4, q_5, q_6 .

3.1 Method. Figure 2 shows a sketch of the exoskeleton on the shoulder complex. Five cables are routed through the shoulder cuff which terminate on the upper arm cuff. The lengths of these cables are accurately measured using motor encoders and are used in the computation.

The following notations are used throughout the text:

S_i, U_i : Attachment points of cable i , $i = 1, 2, \dots, 5$ on the shoulder cuff and upper arm cuff, respectively.

${}^i\overline{AB}$: Vector from point A to point B in local coordinate frame of link i , $i = 0, 1, \dots, 6$.

${}^i\overline{P}$: Vector ${}^i\overline{O_iP}$, $i = 0, 1, \dots, 6$.

l_i : Length of cable i , $i = 1, 2, \dots, 5$.

Fig. 2 A sketch of shoulder complex with the exoskeleton. O_0 is the origin of inertial frame. O_6 is the origin of upper arm local coordinate frame. G is the glenohumeral joint rotation center. S_i and U_i are cable attachment points of cable i on the shoulder cuff and upper arm cuff, respectively. l_i is the length of cable i .

R_i^j : Rotation matrix which expresses the orientation of $O_jX_jY_jZ_j$ relative to $O_iX_iY_iZ_i$, $i, j = 0, 1, 2, \dots, 6$.

The goal is to find the position of GH-c in the inertial frame, i.e., ${}^0\overline{G} = [q_1, q_2, q_3]^T$. For cable i , the following equations can be obtained

$${}^0\overline{U}_i = {}^0\overline{G} + R_0^6 \cdot {}^6\overline{GU}_i \quad (1)$$

$$l_i = |{}^0\overline{U}_i - {}^0\overline{S}_i| \quad (2)$$

Substituting Eq. (1) into Eq. (2) yields

$$l_i = |{}^0\overline{G} + R_0^6 \cdot {}^6\overline{GU}_i - {}^0\overline{S}_i| \quad (3)$$

In Eq. (3), l_i can be computed using the motor shaft angle. It can be shown that R_0^6 is a function of shoulder joint angles q_4, q_5 , and q_6 , which can be obtained from the orientation sensor. ${}^6\overline{GU}_i = {}^6\overline{U}_i - {}^6\overline{G}$ and ${}^0\overline{S}_i$ is the position of cable attachment points on the shoulder cuff. These are already known. Therefore, the only unknown in the Eq. (3) is ${}^0\overline{G}$. On defining $[a_i, b_i, c_i]^T = {}^0\overline{S}_i - R_0^6 \cdot {}^6\overline{GU}_i$ and squaring both sides, Eq. (3) can be rewritten as

$$l_i^2 = (q_1 - a_i)^2 + (q_2 - b_i)^2 + (q_3 - c_i)^2. \quad (4)$$

Since five cables are used in this computation, five equations of the above form can be obtained

$$\begin{aligned} l_1^2 &= (q_1 - a_1)^2 + (q_2 - b_1)^2 + (q_3 - c_1)^2, \\ l_2^2 &= (q_1 - a_2)^2 + (q_2 - b_2)^2 + (q_3 - c_2)^2, \\ l_3^2 &= (q_1 - a_3)^2 + (q_2 - b_3)^2 + (q_3 - c_3)^2, \\ l_4^2 &= (q_1 - a_4)^2 + (q_2 - b_4)^2 + (q_3 - c_4)^2, \\ l_5^2 &= (q_1 - a_5)^2 + (q_2 - b_5)^2 + (q_3 - c_5)^2 \end{aligned} \quad (5)$$

${}^0\overline{G}$ is found by solving Eq. (5) for q_1, q_2 , and q_3 .

3.2 Algorithm for Real-Time Implementation. Theoretically, assuming a perfect model and measurements, Eq. (5) would yield a unique solution for ${}^0\vec{G} = [q_1, q_2, q_3]^T$. In order for real-time implementation, Eq. (5) should be solved in an efficient manner.

In fact, each equation in Eq. (5) analytically describes a sphere with radius l_i and center at $C_i = [a_i, b_i, c_i]^T$. Therefore, ${}^0\vec{G}$ can be interpreted as the common intersection of a set of five spheres described by Eq. (5). We understand that the intersection of two spheres leads to a circle. Three spheres intersect at two points. Therefore, if we pick any three spheres from the set, we can find a pair of candidates for ${}^0\vec{G}$ by computing their intersecting points. The intersecting points of three spheres can be found using analytical geometry. If we consider all combinations of three spheres in the set, ${}^5C_3 = 10$ pairs of candidates can be found with a common point ${}^0\vec{G}$.

Due to the use of incremental encoders on the motor shaft, cable lengths must be measured and initialized before training. Inevitably, there will be measurement errors in cable lengths. The orientation sensor measures shoulder joint angles by fusing data from magnetometers, accelerometers and gyros. It has approximate inaccuracy of two degrees in the joint angle measurement during dynamic movements. Also, the design parameters may have errors due to machining and assembly tolerances. All these factors may lead to a possibility that Eq. (5) has no solution, i.e., the ten pairs of candidates of ${}^0\vec{G}$ need not share a common point. However, we expect that these candidates may have a cluster around the actual ${}^0\vec{G}$, given that the measurement and parameter errors are usually small (Fig. 3). The best estimate of ${}^0\vec{G}$, i.e., the location of glenohumeral joint rotation center, can be obtained by averaging the clustered candidates.

It is important to note that, there will be ten candidates in the cluster, one from every pair. However, it is possible that a combination of three spheres do not have any intersecting points due to errors. In this case, the combination should be discarded. Also, it is possible that in some configurations, there will be two clusters of candidates, each with half of the candidates, so that one may not be able to distinguish to which clusters the GH-c should belong. In this case, the estimate from the previous time instance should be used as a reference since the movement of GH-c is continuous.

Finally, a flowchart of the algorithm is shown in Fig. 4. This algorithm requires less than 1ms on a Pentium M 2.0 GHz processor real-time controller, which is sufficient for real-time application. The estimation method requires at least three cables, however, more cables improve both the robustness and accuracy of the estimation.

Fig. 3 Two dots connected by a dash line represent a pair of candidates for GH-c. (a) The ideal case: Every pair of candidates shares a common point for GH-c. (b) The actual case: One of the candidates of every pair clusters around the actual position of GH-c.

4 Simulation

As mentioned in Sec. 3.2, joint angle measurement from the orientation sensor has noise of about two degrees. The cable length measurement also has error due to initial manual measurement. Simulation was first carried out to validate the proposed algorithm under these measurement uncertainties.

In the simulation, the GH-c was assumed to be fixed at $G = (-0.05, 0, -0.03)^T$ (unit: m), a typical approximate position with a subject wearing the exoskeleton. White noise of two degree

Fig. 4 Flowchart of the GH-c estimation algorithm

Fig. 5 Top row: Estimated GH-c trajectory in the presence of joint angle measurement noise and cable length measurement error. Middle row: Estimation error of GH-c. Bottom row: Shoulder joint angles q_1 , q_2 , q_3 .

amplitude was added to the joint angles. The corresponding cable length trajectories were computed. A constant offset $\mathbf{L}_{\text{offset}} = (0.01, -0.005, 0.0008, 0.01, -0.01)$ (unit: m) was added to the computed cable lengths. These simulated measurements were used to reconstruct the GH-c trajectory using the proposed algorithm. The result is shown in Fig. 5. The result shows that the error in the computed GH-c trajectory was less than 1.5 cm in all the three coordinates. The algorithm demonstrated robustness against measurement errors.

Fig. 6 Estimated GH-c path compared to a model

5 Experiment

Experiments were performed to verify the proposed estimation algorithm in practical application. We obtained the path of the GH-c in a test motion and compared it to a model proposed by Nef et al. [5]. The subject was tied to the chair with a super wrap to constrain trunk motion. The subject abducted his arm in the frontal plane to the highest he can. The subject lifted his arm six times and the GH-c paths of the trials were normalized and averaged. The results are shown in Fig. 6. The estimated GH-c path roughly matches the model. The difference between the two may be because: (1) Slight trunk motion was present in the test motion. The GH-c estimation proposed in this paper estimates the location of the GH-c relative to the inertial frame. This is a combination of the movement of the GH-c relative to the trunk and the trunk motion relative to the inertial frame; (2) The model was obtained from CT data of a single subject and scaled for different subjects. The model was also not extensively evaluated; (3) The algorithm is based on a kinematic model where the cuffs are rigidly connected to the arm, however there inevitably exists motion between the cuffs and the skeleton due to soft tissues; however, such motion is small due to the fact that the orthoses on upper arm and forearm are connected with a hinge.

6 Conclusion

In this paper, we presented a novel approach to estimate glenohumeral joint rotation center (GH-c) in order to improve the accuracy of the kinematic model and the training performance with CAREX. A kinematic model of the exoskeleton that takes the GH-c translation into account was developed. The method for GH-c estimation was first described. Practical issues in the implementation due to sensor and measurement uncertainties were addressed. An algorithm for practical application of the method in real-time was presented. Simulation was first carried out to

successfully validate the algorithm with the presence of joint angle noise and cable lengths measurement error. Experiments were performed to match the estimation results with a model from the literature. Possible causes of mismatch were analyzed.

As further experiments are planned, several open questions need to be addressed. The accuracy of the estimation should be verified using proper instrumentation. The impact of GH-c estimation on the training performance of CAREX with healthy subjects and stroke patients should be further investigated.

Acknowledgment

This project was supported by the Delaware INBRE program, with grants from the National Center for Research Resources - NCRR (5P20RR016472-12) and the National Institute of General Medical Sciences - NIGMS (8 P20 GM103446-12) from the National Institutes of Health.

References

- [1] Prange, G. B., Jannink, M. J. A., Groothuis-Oudshoorn, C., Hermens, H. J., and IJzerman, M. J., 2006, "Systematic Review of the Effect of Robot-Aided Therapy on Recovery of the Hemiparetic Arm After Stroke," *J. Rehabil. Res. Dev.*, **43**(2), pp. 171–184.
- [2] Kwakkel, G., Kollen, B. J., and Krebs, H. I., 2008, "Effects of Robot-Assisted Therapy on Upper Limb Recovery After Stroke: A Systematic Review," *Neuro-rehabilitation Neural Repair*, **22**(2), pp. 111–121.
- [3] Krebs, H. I., Hogan, N., Aisen, M. L., and Volpe, B., 1998, "Robot-Aided Neurorehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, **6**(1), pp. 75–87.
- [4] Lum, P., Reinkensmeyer, D., and Lehman, S., 1993, "Robotic Assist Devices for Bimanual Physical Therapy: Preliminary Experiments," *IEEE Trans. Rehabil. Eng.*, **1**(3), pp. 185–191.
- [5] Nef, T., Guidali, M., and Riener, R., 2009, "Armin III—Arm Therapy Exoskeleton With an Ergonomic Shoulder Actuation," *Appl. Bionics Biomech.*, **6**(2), pp. 127–142.
- [6] Frisoli, A., Rocchi, F., Marcheschi, S., Dettori, A., Salsedo, F., and Bergamasco, M., 2005, "A New Force-Feedback Arm Exoskeleton for Haptic Interaction in Virtual Environments," *First Joint Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005*, March 18–20 2005, pp. 195–201.
- [7] Schiele, A., and van der Helm, F., 2006, "Kinematic Design to Improve Ergonomics in Human Machine Interaction," *IEEE Trans. Neural Syst. Rehabil. Eng.*, **14**(4), pp. 456–469.
- [8] Ball, S., Brown, I., and Scott, S., 2007, "Medarm: A Rehabilitation Robot With 5DOF at the Shoulder Complex," *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Sept. 4–7, 2005, Zurich, Switzerland, pp. 1–6.
- [9] Stienen, A., Hekman, E., van der Helm, F., and van der Kooij, H., 2009, "Self-Aligning Exoskeleton Axes Through Decoupling of Joint Rotations and Translations," *IEEE Trans. Rob. Autom.*, **25**(3), pp. 628–633.
- [10] Brackbill, E., Mao, Y., Agrawal, S. K., Annappagada, M., and Dubey, V., 2009, "Dynamics and Control of a 4-DOF Wearable Cable-Driven Upper Arm Exoskeleton," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 2300–2305.
- [11] Agrawal, S. K., Dubey, V. N., John J. Gangloff, J., Brackbill, E., Mao, Y., and Sangwan, V., 2009, "Design and Optimization of a Cable Driven Upper Arm Exoskeleton," *ASME J. Med. Devices*, **3**(3), p. 031004.
- [12] Mao, Y., and Agrawal, S. K., 2010, "Wearable Cable-Driven Upper Arm Exoskeleton-Motion With Transmitted Joint Force and Moment Minimization," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 4334–4339.
- [13] Mao, Y., and Agrawal, S. K., 2011, "A Cable Driven Upper Arm Exoskeleton for Upper Extremity Rehabilitation," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 4163–4168.
- [14] Mao, Y., and Agrawal, S. K., 2012, "Cable Driven Arm Exoskeleton (CAREX): Transition From Experiments on a Mechanical Arm to the Human Arm," *Proceedings of IEEE International Conference on Robotics and Automation*, May 9–13, 2011, Shanghai, China, 4163–4168.
- [15] Mao, Y., and Agrawal, S. K., 2012, "Design of a Cable Driven Arm Exoskeleton (CAREX) for Neural Rehabilitation," *IEEE Trans. Robot.*, **28**(4), pp. 922–931.
- [16] Wu, G., Van Der Helm, F. C. T., (DirkJan) Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., and Buchholz, B., 2005, "ISB Recommendation on Definitions of Joint Coordinate Systems of Various Joints for the Reporting of Human Joint Motion-Part II: Shoulder, Elbow, Wrist, Hand," *J. Biomech.*, **38**, pp. 981–992.
- [17] Perry, J., Rosen, J., and Burns, S., 2007, "Upper-Limb Powered Exoskeleton Design," *IEEE/ASME Trans. Mechatron.*, **12**(4), pp. 408–417.
- [18] Carignan, C., Liszka, M., and Roderick, S., 2005, "Design of an Arm Exoskeleton With Scapula Motion for Shoulder Rehabilitation," *Proceedings of International Conference on Advanced Robotics*, July 18–20, 2005, Seattle, WA, pp. 524–531.