2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob) | 978-1-6654-5849-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/BIOROB52689.2022.9925452

Amyotrophic Lateral Sclerosis Patients Regain Head-Neck Control Using a Powered Neck Exoskeleton

Haohan Zhang[1], *Member, IEEE*, Biing-Chwen Chang[2] *Member, IEEE*, Priya Kulkarni[3] *Student Member, IEEE*, Jinsy Andrews[4], Neil A. Shneider[4], and Sunil Agrawal[3,5,*], *Member, IEEE* .

***Abstract*— A cross-sectional human study was conducted to validate a powered neck exoskeleton to assist with head-neck motions in five head drop patients. Head drop, a condition caused by neck muscle weakness, is commonly seen in patients with neurological disorder, such as amyotrophic lateral sclerosis (ALS). Current clinical practice of using static braces has low acceptance by head drop patients due to their discomfort from these braces and their inability to restore motion. Previously, a powered neck exoskeleton was developed to assist with head-neck motion but its efficacy was not evaluated by patients with head drop. In the present study, ALS head drop patients were recruited to use this exoskeleton and follow prescribed head-neck motions. Their performance with the exoskeleton was compared with their own performance when not receiving any assistance from the exoskeleton. Head orientations and surface electromyography of four select neck muscles were recorded. Outcome variables were derived from these data and compared between the two experimental conditions. We observed that the subjects decreased their motion tracking errors and reduced their neck muscle activation when receiving the robotic assistance. We conclude that the powered neck exoskeleton could help ALS patients regain their head-neck control.**

I. INTRODUCTION

Head drop is a common symptom in patients diagnosed with amyotrophic lateral sclerosis (ALS) [1], [2], [3], [4]. Due to the weakness of their neck muscles, patients present with difficulties in positioning and moving their head-neck in a controlled manner. In extreme cases, the head completely drops, resulting in a chin-on-chest posture. Head drop limits an individual's ability to perform daily functional tasks, such as participating in a conversation, or feeding themselves. Additionally, patients with head drop often report neck pain and suffer from respiratory issues [5], [6], [7], [8]. Prolonged head drop may further result in muscle atrophy.

Static braces are recommended by physicians to support the head [9], [10], [11]. Popular designs use parts that are made of plastic or foam to form an enclosure around the neck to support the head at the chin [12], [13]. However, these braces are often not used over a prolonged time by those with ALS [14] because they are uncomfortable and challenging to wear. The brace is either too tight, causing skin breakdown due to humidity, or too loose, failing to effectively support the head. Current research is mainly focused on improving the comfort of static braces. Sheffield collar, for example, was invented to support the head upright while allowing small movement of the head. This collar was shown to be more comfortable when compared with conventional braces [10]. However, the need of regaining controlled head-neck movements was not addressed for and hence remains unmet.

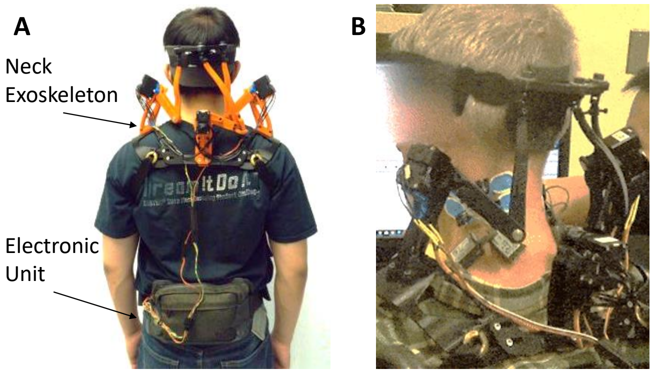

Fig. 1: (A) The powered neck exoskeleton worn by a healthy individual. The structure of the robot is attached between the shoulders and the forehead. The electronics and control unit is housed in a pouch which can be attached to the waist of the user. (B) An ALS subject with head drop using this powered exoskeleton to perform head-neck motions during the present study.

A powered neck exoskeleton was developed in the Rehabilitation and Robotics (ROAR) Laboratory at Columbia University to support head-neck movement (Figure 1). This wearable device weighs less than 1.5 kg and allows up to 70% range of rotation of the head-neck in daily activities [15]. Unlike conventional braces supporting the head under the chin, this device is attached to the forehead through soft fabric and can rest on the shoulders over a pair of pads. All linkages are located on the back of the user so that their field of view is not blocked. This choice also limits the posterior extension, thus prevents hyper-extension of the neck. A novel parallel mechanism was used to design the structure of this robotic device and was then optimized based on the head-neck movement data of human subjects.

A series of studies with healthy subjects have been previously performed to validate the design and control to

---

All studies were performed at the Robotics and Rehabilitation Laboratory at Columbia University. [1]HZ is an Assistant Professor with the Department of Mechanical Engineering at the University of Utah. [2]BC is an Assistant Professor with the Department of Mechanical Engineering at National Taiwan University. [3]PK is a PhD student with the Department of Mechanical Engineering at Columbia University. [4] JA and NAS are faculty members of the Eleanor and Lou Gehrig ALS Center in the Department of Neurology at Columbia University Irving Medical Center. [3,5*]SA is a Professor with the Department of Mechanical Engineering at Columbia University, jointly appointed by the Rehabilitation and Regenerative Medicine at Columbia University Irving Medical Center. Email: `sunil.agrawal@columbia.edu`

[*] Address all correspondence to this author.

assist and retrain head-neck movements [16], [17], [18], [19], [20]. Yet, the efficacy of this powered exoskeleton in assisting ALS head drop patients with head-neck motion remains untested. As a crucial step in moving forward, in this paper, we present a pilot study where this robotic innovation was evaluated by ALS patients who had mild-to-moderate head drop. The focus was to investigate the mechanical integrity of the robot and the user performance when using it.

We show that with the motion assistance provided by the exoskeleton, the participants could move their head over a larger range of motion and achieve more precise control of the motion with lower neck muscle activation. *To the best of our knowledge, this is the first study to demonstrate that ALS patients with head drop can regain coordinated head-neck movements through a powered neck exoskeleton.*

II. METHODS AND MATERIALS

A. Powered Neck Exoskeleton

The powered neck exoskeleton was used both as a measurement and an assistive device in the present study. This robotic device has three degrees-of-freedom and is actuated by three servomotors (Dynamixel XM430-W350-R, ROBOTIS Co. Ltd, Seoul, South Korea). The robot is highly back-drivable due to the choice of the actuators and the kinematics of its structure. The exoskeleton can therefore be used as a motion sensor, i.e., measuring head-neck spatial orientation relative to the shoulders when the motor torques are turned off.

To provide motion assistance, a keyboard control was implemented in this study. The exoskeleton was controlled to make incremental rotations by six different key: forward/backward tilts and bi-directional turns and bends. The step sizes of the increments were controlled by another pair of keys. Inverse kinematics model was then used to compute the motor trajectories based on the user inputs.

B. Subjects

TABLE I: Subject Characteristics

ID	Gender	Age	Height (cm)	Weight (kg)	%FVC[1]
001	M	55	195	91	37
002	M	33	185	116	20
003	F	56	169	73	99
004	M	76	166	69	89
005	M	39	183	110	53

Five ALS subjects (Table I) were enrolled in this study, approved by the Institutional Review Board (IRB) at Columbia University. These subjects were under consultation with the neurologists at the Eleanor and Lou Gehrig MDA/ALS Research Center, Columbia University Irving Medical Center. They had presented or complained about heaviness of the head during their most recent clinical checkup and were recommended by their physicians to participate in this experiment. The diagnoses of ALS of these patients were made based on the El Escorial ALS diagnostic criteria [21], [22], clinical findings [23], [24], and lab testing. Static neck braces or collars were used by three participants (subjects 001, 002, and 005) at the time of the experiment. Four subjects presented with dropped head posture while seated (subjects 001, 002, 004, and 005). One subject reported moderate neck pain (subject 001).

TABLE II: Motion tasks used in this experiment.

Motion Tasks	Functions (Units: SI)
Sagittal Plane Flexion-Extension	$x(t) = 15^\circ \sin(0.2\pi t) - 10^\circ$
Coronal Plane Lateral Bending	$x(t) = 20^\circ \sin(0.2\pi t)$
Transversal Plane Axial Rotation	$x(t) = 25^\circ \sin(0.2\pi t)$

C. Experimental Procedures

After obtaining their consent, each subject was seated in front of a computer screen (Figure 2A). On the screen, we displayed the movement tasks to the subjects through a visual interface (Figure 2B). The prescribed head-neck motion was shown by an avatar (solid). It was overlaid with the actual motion of the subject's head-neck, represented by another avatar (translucent). The powered exoskeleton (Figure 2C) was then aligned and attached to the subject's shoulders and forehead. Soft padding was added, as needed, to ensure comfort and obtain a good fit between the robot and the subject. Additionally, electrodes for surface electromyography (sEMG, DTS, Noraxon USA Inc., Scottsdale, AZ, USA) were placed at the four neck muscles of interest – sternocleidomastoid (SCM) and splenius capitis (SC) on both sides of the neck. The measurement of the EMG was time synchronized with the neck exoskeleton system.

Three prescribed motions were used in this study (Table II): sagittal plane flexion-extension, coronal plane lateral bending, and transversal plane axial rotation. For each motion, the subject followed continuously for five times within a trial. The first and last cycles were discarded from the data analysis. Because the neck exoskeleton was designed to prevent hyper-extension of the head, the range of motion allowed by the brace in extension is much smaller compared to flexion [15]. Therefore, the motion in the sagittal plane was chosen asymmetrically about the neutral upright position. The amplitudes of the motions were selected such that the subjects could see the computer screen while rotating their head. The speeds of motions were chosen to be relatively low so that the subjects were able to understand the motion tasks using the visual interface.

The experiment had two conditions. First, each subject performed the prescribed head-neck motions using their own ability (Baseline condition). The exoskeleton was in its 'transparent mode' to measure the head-neck motion of the subject (Supplemental Video 1). Then, the subject repeated the same motions (Assist condition), aided by the powered exoskeleton through the motion controller (Supplemental Video 2).

Due to neck muscle weakness, in the Baseline condition, some subjects had difficulties to fully reach the desired range of motion or to continue a motion that was in opposite

---

[1] %FVC is percentage forced vital capacity.

direction to gravity (e.g., flexion/extension). Hence, during this session, an experimenter stood by and placed the hands around the subject's head to gently support the head and prevent it from falling. Due to the progression of the disease, some subjects had developed weakness in their upper extremity. Thus, pressing the keys on the keyboard was not practical for them. During the Assist condition, a designated experimenter watched the screen and pressed the keys for the subjects to follow the prescribed motion. The experimenter was kept the same across all five subjects. The subjects were encouraged to rely on the motion provided by the neck brace during the Assist condition.

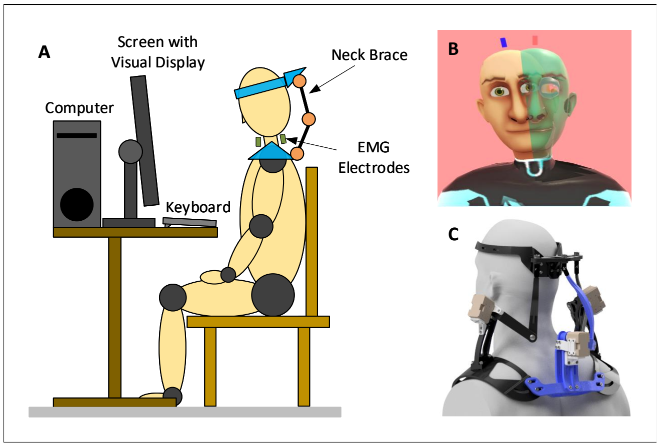

Fig. 2: (A) A schematic of the experimental setup. The subject was seated in front of a computer screen with an avatar interface. The neck exoskeleton and the surface EMG electrodes were attached to the individual. (B) The computer screen displayed the desired and actual head motions through two avatars. The translucent avatar indicates the actual head motion of the user, measured by the exoskeleton, while the avatar with solid colors showed the desired planar movement of the head-neck. Bar indicators placed on top of the heads of the avatars updated the tracking accuracy with color changes. (C) The structure of the powered neck exoskeleton. This robot attaches to the shoulders and forehead of the user, measures the head-neck movements through encoders, and assists with the head-neck motions through three servomotors.

Prior to each experimental condition, verbal instructions were given to the subjects. They were then allowed to practice and familiarize themselves with the tasks and the system. This period lasted for up to five minutes. A static trial was performed to record the head-neck posture and muscle activities while the head was in the upright neutral configuration. This step provided a reference for the head kinematics and neck muscle EMGs at rest.

D. *Data Processing and Analysis*

The independent variables in this study included the experimental condition (Baseline vs. Assist), the movement plane (Sagittal, Coronal, and Transversal), and the muscle channels (lSCM, rSCM, lSC, rSC). The outcome (dependent) variables were derived from the head kinematics and the neck muscle activation, collected by the neck exoskeleton (50 Hz) and the surface EMG sensors (1.5 kHz), respectively. The kinematic data were low-pass filtered at 10 Hz. The EMG data were de-trended and band-pass filtered between 3 and 450 Hz, followed by a full wave rectification.

For the dependent variables, we use a representative data (Figure 3) to illustrate these variables:

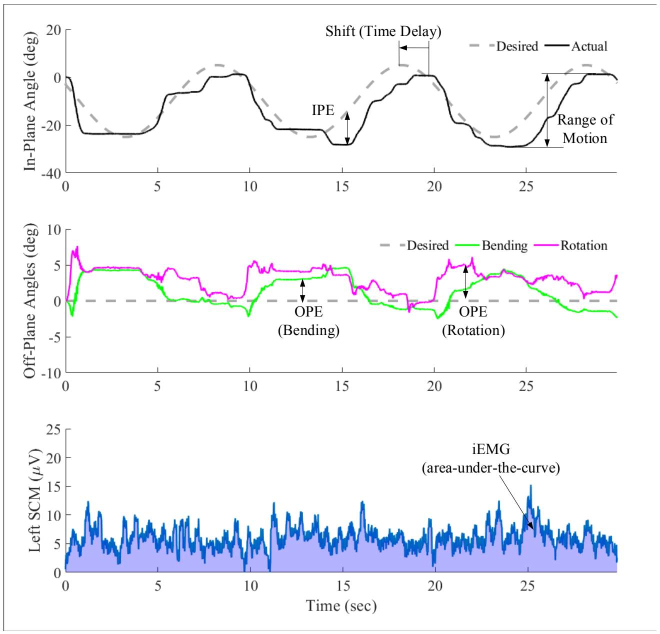

Fig. 3: Kinematic and EMG outcome variables from a subject during sagittal plane flexion-extension: (Top) Desired (grey dashed) and actual (black) movement of the head-neck in sagittal plane. The difference between the maximum and minimum value of the actual movement in the sagittal plane denotes the range of motion of the subject during this trial. To compute IPE, the actual movement was first shifted to be aligned with the desired signal. (Middle) Out-of-plane movements of the head. (Bottom) Filtered EMG of the left SCM (blue) where the iEMG is the area under the curve (shaded blue).

In-plane tracking error (IPE): This variable was defined as the root mean square (RMS) error of the actual head-neck motion compared to the prescribed motion in the desired movement plane, during the three motion cycles recorded. To eliminate the time delay when reacting to the target movement, the signals were aligned in software prior to computing this variable. This variable evaluates the ability to follow the movement within the desired plane.

Out-of-plane error (OPE): There are two out-of-plane rotations when tracking a single plane motion. It is the lateral bending and the axial rotation during a sagittal plane motion, for example, as shown in Figure 3. The OPE was defined as the maximum value of the absolute mean of these two angles, during the three motion cycles recorded. This variable assesses the ability to control the head to move within the desired plane.

Range of motion error (RME): This was defined as the absolute difference of the motion ranges between the desired and the actual movements within the desired plane, during the three cycles recorded. The desired ranges of motion can be computed from the desired motions in Table II. The actual ranges of motion were obtained by the arithmetic difference between the maximum and minimum value of the actual motion. This variable quantifies the ability to coordinate movements within the specified range.

Integrated EMG (iEMG): This variable was defined as the area under the curve of the EMG from a specific muscle during the three motion cycles recorded in each trial. It is used to infer the amount of muscle input from the subject during a movement.

We hypothesized that all outcome variables, i.e., the IPE, OPE, RME, and iEMG, decrease among the subjects while performing the tasks assisted by the neck exoskeleton. Due to the small sample size and heterogeneity among the subjects, non-parametric tests were used. Wilcoxon signed-rank test was performed to investigate the effects of the experimental conditions on the outcome measures. The influence of the movement directions and the muscle groups were examined using Friedman test. Additionally, the effects of the consistency of the designated experimenter who pressed the keyboard during the Assist condition on variables of head kinematics (IPE, OPE, and RME) were tested using Kruskal-Wallis test. Matlab (R2018b, MathWorks Inc., Natick, MA, USA) was used to perform the statistical analysis. The statistical significance threshold was set at $p < 0.05$.

III. RESULTS

Individual performances of these five subjects are summarized in Table III. Except for subject 001, all subjects were able to complete the Baseline condition against gravity without receiving support from the experimenter. When aided by the neck exoskeleton, all five subjects were able to complete the movement tasks of the head-neck.

The subjects can be roughly categorized into three levels based on their performances. Subject 001 was not able to complete the motions as this individual needed gentle push from the experimenter to continue the task and had a small range of motion. When aided by the exoskeleton, the range of motion of the head-neck of this individual increased significantly. Subjects 002, 004, and 005 were able to complete the tasks on their own during Baseline. When supported by the exoskeleton, their tracking performance gained moderate improvements with lower muscle activation. Subject 003 out-performed other participants during Baseline. The muscle EMG of this subject reduced significantly by 46.9% when assisted by the robotic brace.

The IPE was found to be significantly lower in the Assist than the Baseline condition (Median = 2.67°, IQR = $-0.69^\circ \sim 5.63^\circ$; $p = .008$). The movement planes of the tasks had little effect on IPE (Chi-square = 3.79; $p = .15$). The OPE was also found to be significantly lower in the Assist than the Baseline condition (Median = 3.11°, IQR = $1.01^\circ \sim 5.45^\circ$; $p = .002$). The change of movement planes did not influence the OPE (Chi-square = 2.08; $p = .35$). Additionally, the RME was reduced in the Assist condition, as compared to the Baseline condition. This reduction was found to be significant (Median = 9.21°, IQR = $4.62^\circ \sim 12.90^\circ$; $p < .001$) regardless of the movement planes (Chi-square = 4.75; $p = .093$).

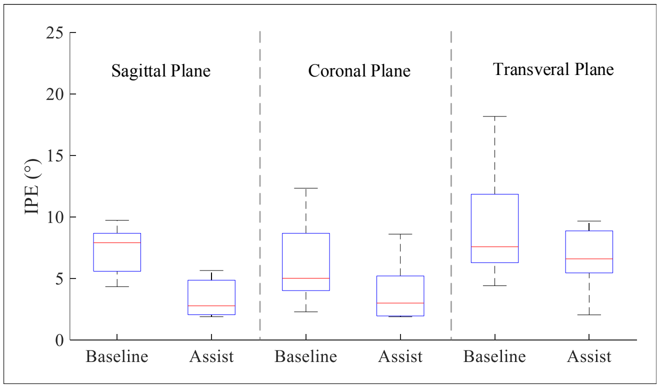

Fig. 4: A box plot for the in-plane tracking error (IPE), compared between two conditions during head-neck movements in three anatomical planes.

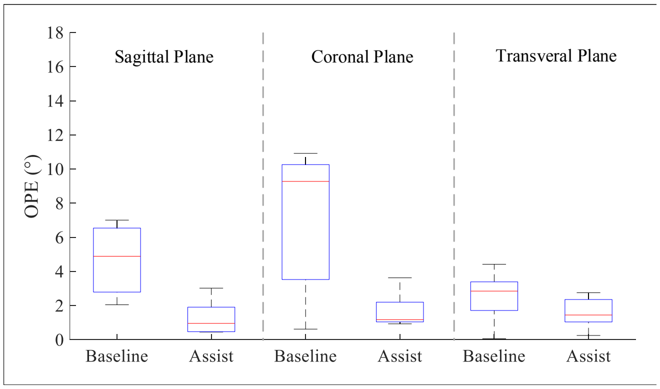

Fig. 5: A box plot for the out-of-plane tracking error (OPE), compared between two conditions during head-neck movements in three anatomical planes.

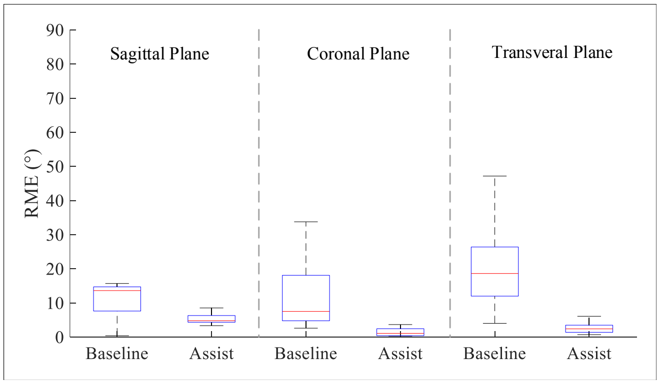

Fig. 6: A box plot for the range-of-motion error (RME), compared between two conditions during head-neck movements in three anatomical planes.

The iEMG was found to be significantly reduced when the head-neck was supported by the exoskeleton (Median = $68.03\mu \cdot Vs$, IQR = $26.18 \sim 106.99\mu \cdot Vs$; $p < .001$) during both the static (i.e., holding the upright posture) and the dynamic tasks. This was consistent across all four muscles (Chi-square = 0.21, $p = 0.98$).

Kruskal-Wallis test revealed that when assisted by the exoskeleton, the head kinematics were not significantly differ-

TABLE III: Individual subject performances.

			IPE (○)	OPE (○)	RME (○)	iEMG ($\mu V \cdot s$)			
						lSCM	rSCM	lSC	rSC
001	Sagittal	Baseline[2]	9.7	4.9	14.4	212.8	167	168.1	247.8
		Assist	4.6	1.5	4.8	177.8	110	136.2	215.3
	Coronal	Baseline	12.3	0.6	33.8	193	249.4	125.9	207.5
		Assist	2	1.1	2	142.8	162.9	76.7	176.7
	Transversal	Baseline	18.2	0.1	47.2	170.8	322.5	132	220.7
		Assist	9.6	2.8	2.6	152	183.8	125.1	183.3
002	Sagittal	Baseline	6	3	0.4	296.5	210.3	490.1	563.5
		Assist	2.8	0.9	4.7	220.5	199.1	404.7	498.6
	Coronal	Baseline	7.4	10.9	12.9	301.7	267.1	495.5	550.8
		Assist	8.6	3.6	3.7	206.1	168.3	355.7	405.8
	Transversal	Baseline	7.6	4.4	14.7	371	336.8	477.8	514.8
		Assist	8.6	1.3	1.6	160.3	169.8	354.7	417.5
003	Sagittal	Baseline	8	6.4	15.7	171.2	89.6	214.3	215.9
		Assist	2.1	0.5	3.3	83.3	77.8	134.8	139.1
	Coronal	Baseline	5	4.5	7.5	292.1	312.7	155.7	186.8
		Assist	3	0.9	0.4	125.1	247.6	102.3	115.5
	Transversal	Baseline	6.9	2.3	19.5	216.2	456.1	152.8	226
		Assist	6.6	1.4	0.7	114.4	82.4	91.5	113.9
004	Sagittal	Baseline	4.3	2	10	108.6	133.3	170.1	128.1
		Assist	1.9	0.5	5.6	123.8	137.9	174	136
	Coronal	Baseline	4.6	10	5.5	247.3	438.1	191.9	121
		Assist	1.9	1.7	0.3	116.5	237.2	147.4	112.9
	Transversal	Baseline	4.4	3	4	122.3	251.8	230.2	132
		Assist	6.6	2.2	2.4	115.5	151.8	159.2	125
005	Sagittal	Baseline	8.3	7	13.6	534.7	246.6	216.6	143.2
		Assist	5.6	3	8.5	148.1	168.9	212.1	121.6
	Coronal	Baseline	2.3	9.3	2.6	585.7	200	225.7	135.4
		Assist	4.1	1.2	1.1	173.9	128.1	167.2	132.5
	Transversal	Baseline	9.7	2.8	18.6	607.9	275	227.1	146.3
		Assist	2	0.2	6.1	168.6	128.4	174.4	135.6

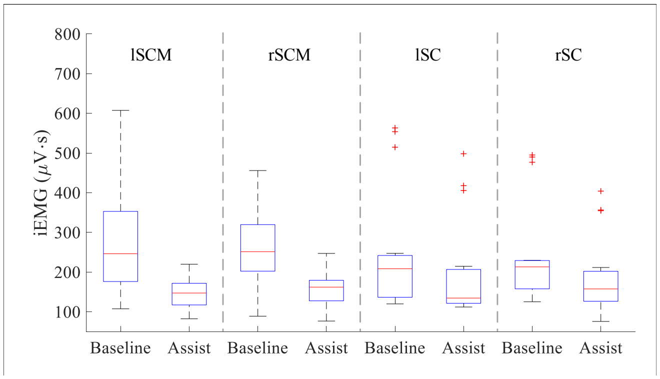

Fig. 7: A box plot for the integrated EMG (iEMG), compared between two conditions across four neck muscles.

ent among subjects. The IPE (Chi-square = 3.23; $p = 0.52$), OPE (Chi-square = 2.17; $p = 0.71$), and RME (Chi-square = 3.3; $p = 0.51$) were all similar regardless of subjects. These results suggest that the designated experimenter performed consistently to press the keyboard to control the exoskeleton.

IV. DISCUSSION

The main objective of this paper was to evaluate a powered neck exoskeleton to assist with head-neck motions for ALS head drop patients. A human study was conducted where the head kinematics and neck muscle EMG of five ALS patients with mild-to-moderate head drop were recorded when using the exoskeleton. The subjects were asked to follow desired three single-plane head-neck movements, aided by the powered exoskeleton. Their performance was compared with their own baseline when they completed the same movements by relying on their own neck muscle strength.

Holding the head upright is a simple task for a healthy individual. It requires the neck muscles, flexors and extensors, to coordinate so that the stability of the head can be maintained under gravity. This task, however, becomes progressively challenging for ALS patients. Our data (i.e., iEMG) suggest that the powered neck exoskeleton supported the head for these subjects to stay upright with much lower muscle activation of their own.

During three single-plane motions, the head kinematics, quantified by the IPE, OPE, and RME, improved when the head-neck was aided by the exoskeleton. Meanwhile, the neck muscle activation of the subjects, quantified by the iEMG, was also found to be much lower across neck muscles when using the powered exoskeleton. These results suggest that this robotic device effectively decreased the muscle inputs from the subjects while helping them complete the tasks.

The desired movements were displayed on a computer screen and cued by avatars. This design provided visual feedback and was easy to understand by the subjects. Like a metronome, it helped set the pace but it also offered richer visual information for the subjects to make adjustments during the tasks.

---

[2] The experimenter supported the subject to avoid falling of the head during the experiment.

With the progression of ALS, patients lose muscle strength and functional range of motion to perform head-neck motions. As seen in the enrolled subjects, for example, patients with weaker neck muscles had more difficulty to follow the prescribed movements. Unlike conventional static braces, we demonstrated that the powered neck exoskeleton can support the head-neck and help head drop patients regain coordinated movements and range of motion. As commented by some of the subjects, this robotic solution could potentially enable them to socialize with others. It could also help them stretch the neck muscles to gain range of motion and relieve neck pain.

A keyboard interface was used in this study to control the neck exoskeleton. Due to the weakness of the upper extremity, however, a few patients could not press on the keys or react fast enough to use this interface. An experimenter was designated to press the keys to command the brace, based on the experimenter's perception of the tasks and the familiarity of the keyboard. We show that the performance delivered by this experimenter remained consistent across all five subjects. Nevertheless, simple but intuitive input devices need to be integrated with this wearable robot to allow a patient to control intended head-neck movements on their own. Special keyboards with bigger keys and wearable eye-trackers could potentially be options [25].

V. CONCLUSIONS

This paper investigated the efficacy of a powered neck exoskeleton to assist with head-neck motions for ALS patients with head drop. While performing head-neck tracking tasks without and with the assistance of the exoskeleton, the head kinematics and neck muscle EMG were compared in five ALS subjects with mild-to-moderate head drops. The results suggest that these participants improved tracking with lower muscle activation while aided by the powered exoskeleton. We believe that this robotic device can assist with head-neck motions for ALS head drop patients, potentially improving their quality of life.

VI. ACKNOWLEDGMENT

We acknowledge research support from ALS Association (Grant #21-MALS-568) and Columbia University School of Engineering STAR program.

REFERENCES

[1] M. Gourie-Devi, A. Nalini, and S. Sandhya, "Early or late appearance of "dropped head syndrome" in amyotrophic lateral sclerosis," *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 74, no. 5, pp. 683–686, 2003.

[2] R. A. Smith and F. H. Norris, "Symptomatic care of patients with amyotrophic lateral sclerosis," *Jama*, vol. 234, no. 7, pp. 715–717, 1975.

[3] T. G. Petheram, P. G. Hourigan, I. M. Emran, and C. R. Weatherley, "Dropped head syndrome: a case series and literature review," *Spine*, vol. 33, no. 1, pp. 47–51, 2008.

[4] G. A. Suarez and J. J. Kelly, "The dropped head syndrome," *Neurology*, vol. 42, no. 8, pp. 1625–1625, 1992.

[5] V. Dal Bello-Haas, A. D. Kloos, and H. Mitsumoto, "Physical therapy for a patient through six stages of amyotrophic lateral sclerosis," *Physical therapy*, vol. 78, no. 12, pp. 1312–1324, 1998.

[6] S. Pinto and M. De Carvalho, "Motor responses of the sternocleidomastoid muscle in patients with amyotrophic lateral sclerosis," *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine*, vol. 38, no. 4, pp. 1312–1317, 2008.

[7] R. Nakamura, N. Atsuta, H. Watanabe, A. Hirakawa, H. Watanabe, M. Ito, J. Senda, M. Katsuno, F. Tanaka, Y. Izumi, *et al.*, "Neck weakness is a potent prognostic factor in sporadic amyotrophic lateral sclerosis patients," *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 84, no. 12, pp. 1365–1371, 2013.

[8] S. Pinto, A. Pinto, and M. de Carvalho, "Phrenic nerve studies predict survival in amyotrophic lateral sclerosis," *Clinical neurophysiology*, vol. 123, no. 12, pp. 2454–2459, 2012.

[9] P. Glazener, "Pilot study to determine the effectiveness of a new neck brace design for patients with amyotrophic lateral sclerosis," *Journal of Nursing Education and Practice*, vol. 4, no. 6, p. 1, 2014.

[10] S. Pancani, J. Rowson, W. Tindale, N. Heron, J. Langley, A. D. McCarthy, A. Quinn, H. Reed, A. Stanton, P. J. Shaw, *et al.*, "Assessment of the sheffield support snood, an innovative cervical orthosis designed for people affected by neck muscle weakness," *Clinical Biomechanics*, vol. 32, pp. 201–206, 2016.

[11] V. A. Cwik, "Als clinical motor signs and symptoms," in *Amyotrophic Lateral Sclerosis*, pp. 131–148, CRC Press, 2005.

[12] A. N. Tescher, A. B. Rindflesch, J. W. Youdas, R. W. Terman, T. M. Jacobson, L. L. Douglas, A. G. Miers, C. M. Austin, A. M. Delgado, S. M. Zins, *et al.*, "Comparison of cervical range-of-motion restriction and craniofacial tissue-interface pressure with 2 adjustable and 2 standard cervical collars," *Spine*, vol. 41, no. 6, pp. E304–E312, 2016.

[13] K. Barati, M. Arazpour, R. Vameghi, A. Abdoli, and F. Farmani, "The effect of soft and rigid cervical collars on head and neck immobilization in healthy subjects," *Asian spine journal*, vol. 11, no. 3, p. 390, 2017.

[14] M. E. Toms, "Patients with als: Empowerment through hospice care," *American Journal of Hospice Care*, vol. 7, no. 3, pp. 32–34, 1990.

[15] H. Zhang and S. K. Agrawal, "Kinematic design of a dynamic brace for measurement of head/neck motion," *IEEE Robotics and Automation Letters*, vol. 2, no. 3, pp. 1428–1435, 2017.

[16] H. Zhang and S. K. Agrawal, "An active neck brace controlled by a joystick to assist head motion," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 37–43, 2017.

[17] H. Zhang, K. Albee, and S. K. Agrawal, "A spring-loaded compliant neck brace with adjustable supports," *Mechanism and Machine Theory*, vol. 125, pp. 34–44, 2018.

[18] H. Zhang, *A novel robotic platform to assist, train, and study head-neck movement*. PhD thesis, Columbia University, 2019.

[19] H. Zhang, B.-C. Chang, Y.-J. Rue, and S. K. Agrawal, "Using the motion of the head-neck as a joystick for orientation control," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 27, no. 2, pp. 236–243, 2019.

[20] H. Zhang, V. Santamaria, and S. Agrawal, "Applying force perturbations using a wearable robotic neck brace," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4197–4202, IEEE.

[21] B. R. Brooks, "El escorial world federation of neurology criteria for the diagnosis of amyotrophic lateral sclerosis. subcommittee on motor neuron diseases/amyotrophic lateral sclerosis of the world federation of neurology research group on neuromuscular diseases and the el escorial" clinical limits of amyotrophic lateral sclerosis" workshop contributors," *Journal of the neurological sciences*, vol. 124, pp. 96–107, 1994.

[22] B. Brooks, R. Miller, M. Swash, and T. Munsat, "El escorial revisited: critérios revistos para o diagnóstico de esclerose lateral amiotrófica," *Esclerose Lateral Scler Outros Motor Neuron Disord*, vol. 1, pp. 293–299, 2000.

[23] B. Swinnen and W. Robberecht, "the phenotypic variability of amyotrophic lateral sclerosis. nat rev neurol. 2014; 10: 661-70."

[24] W.-K. Kim, X. Liu, J. Sandner, M. Pasmantier, J. Andrews, L. Rowland, and H. Mitsumoto, "Study of 962 patients indicates progressive muscular atrophy is a form of als," *Neurology*, vol. 73, no. 20, pp. 1686–1692, 2009.

[25] B.-C. Chang, H. Zhang, E. Trigili, and S. K. Agrawal, "Bio-inspired gaze-driven robotic neck brace," in *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, pp. 545–550, IEEE, 2020.