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Applying Force Perturbations Using a Wearable Robotic Neck Brace

Haohan Zhang[1,#], *Student Member, IEEE, Victor Santamaria*[1,#], *and Sunil Agrawal*[1,*], *Member, IEEE*

***Abstract*— Force perturbation is used in this paper to study cervical neuromuscular responses which can be used in the future to assess impairments in patients with neurological diseases. Current literature on this topic is limited to applying forces on the head in the anterior-posterior direction, perhaps due to technological limitations. In this paper, we propose to use a robotic neck brace to address these shortcomings due to its lightweight portable design and the ability to control forces. A controller is implemented to apply direction-specific perturbations on the head. To demonstrate the effectiveness of this capability, a human study was carried out with able-bodied subjects. We used this robotic brace to apply forces on the head of the subjects and observed their movement and muscle responses both when their eyes were open and closed. Our results suggest that the robotic brace is capable of perturbing the head and tracking the kinematic response. It revealed that able-bodied subjects reacted to the perturbations differently when their eyes were closed. They showed longer head trajectories and more muscle activation when the eyes were closed. We also show that the direction-specific perturbation feature enables us to analyze kinematic and muscle variables with respect to the direction of perturbation. This helps better understand the neuromuscular response in the head-neck.**

I. INTRODUCTION

Stabilizing the head-neck under perturbations is a task that we routinely perform in our daily life. Imagine sitting in a moving vehicle on an uneven terrain, we are able to keep balance of the head and maintain a proper posture. This is because our central nervous system quickly reacts to the perturbations and commands the neck muscles to stabilize the head. The same, however, cannot be said for individuals with neural impairments. Amyotrophic lateral sclerosis (ALS) patients with head drop, for example, use rigid cervical collars to keep their head upright while being transported in a vehicle. In clinics, physicians use their hands to gently push the head of patients with cerebral palsy (CP) and visually assess the impairment based on the patient's response. However, such an evaluation may be subjective and heavily depends on the experience of the treating physician.

Using perturbation techniques to study head-neck control also has scientific value. Applying small forces on the head to observe its reactive control, for example, can help researchers understand the association between strength and neuromuscular response of the neck muscles [1]. In the literature, different perturbation methods have been developed to assess and study reactive head control. These methods can be categorized as load dropping [1], [2], [3], quick release [4], [5], and direct contact [6], [7]. Due to the design, size, and weight, however, reconfiguring these devices to apply forces in different directions or amplitudes is almost impossible. Due to these technological limitations, current data are limited to only observations in the anterior-posterior direction.

We propose to use a robotic neck brace to perform small force perturbations on the head. This wearable robot was developed in the Robotics and Rehabilitation (ROAR) Laboratory at Columbia University and has been successfully used in a variety of applications [8], [9], [10], [11], [12], [13]. Although the ability of this robot to command a desired force has previously been validated [11], it has not yet been used to study human perturbation responses. In this paper, we program this brace to apply direction-specific impulsive forces on the head so that it can be used as a tool to study reactive head-neck control.

To demonstrate its effectiveness, we carried out a human experiment with able-bodied subjects. Perturbations were given to these individuals' head in eight different directions in a random order. Subjects underwent the same protocol with their eyes closed and then eyes open. Vision plays a prominent role in balance. Hence, we hypothesized that the robotic brace can measure the response when the visual condition is altered. The results revealed that the absence of vision makes it more difficult for subjects to rebalance their head. In fact, subjects adopted a different strategy with longer path and increased muscle activation in the absence of vision. We also found direction-specific features in their responses.

In this paper, we first provide a brief overview of the technology. This is followed by the details of the human evaluation and our approach to analyze the data. The key findings are then summarized and discussed. The main contribution of this paper is to apply a portable robotic device to provide controllable force perturbations on the head. This module can potentially be used in scientific explorations, clinical assessment, and training of the head-neck control.

II. METHODS AND MATERIALS

A. Hardware

The robotic neck brace allows roughly 70% of the head-neck rotation while accommodating a small translation of the head [8]. We have used this brace to assist head-neck motion in different studies involving able-bodied subjects [9], [10], [11], [12] and ALS patients [13]. In this paper, we use this robotic brace to apply small force perturbations on the head in able-bodied subjects.

[1] HZ is a postdoctoral researcher, VS is an associate research scientist, and SA is a professor. All authors are with the Department of Mechanical Engineering, Columbia University, New York, NY 10027. SA also has a joint appointment with the Department of Rehabilitation and Regenerative Medicine at Columbia University Medical Center, New York, NY 10032. sunil.agrawal@columbia.edu
[#] Joint authors equally contributed to this paper.
[*] Address all correspondence to this author.

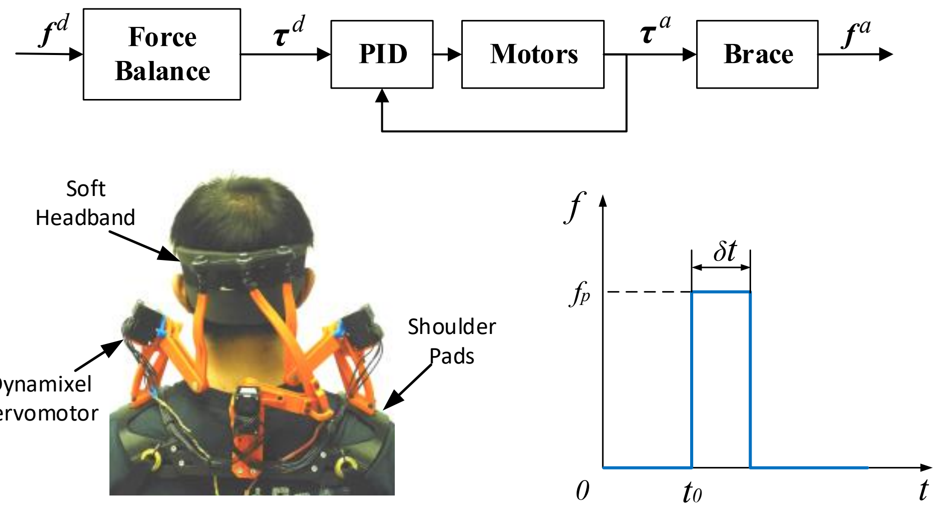

Fig. 1: (Top) Schematics of the force controller, where f^d and τ^d denote desired force and joint torques, and τ^a, f^a, θ^a, and x^a denote actual joint torques, actual force, actual joint angles, and actual orientation of the end-effector, respectively. (Bottom Left) The neck brace worn by a human user. The base of the neck brace is set to be within the shoulders of the user, with left-right as the x axis and posterior-anterior as the y axis. (Bottom Right) An impulsive force with respect to time. The pulse width is denoted as δt and the magnitude of the pulse as f_p.

In its current form (Figure 1 Bottom Left), the robot is actuated by three servomotors (Dynamixel XM430-W350-R, ROBOTIS, Seoul, South Korea) which communicate with the microcontroller (NI myRIO-1900, National Instruments, Austin, Texas, USA) through a serial protocol (RS-485). The brace is attached to the shoulders and the forehead using a pair of 3D-printed pads and a soft strap, respectively. The use of soft materials makes the brace comfortable to wear for extended periods of time. The linkages are 3D printed and the mechanical joints, i.e., revolute and spherical joints, are realized with off-the-shelf components.

B. Controller

We use a force controller to apply perturbations (Figure 1 Top). To generate a three-dimensional force at a reference point on the end-effector, joint torques are computed using a quasi-static model [14] based on the principle of virtual work. These joint torques are determined by the current readings in the servomotors which are controlled by internal PID controllers.

The forcing function chosen chosen in this study is an impulsive force (Figure 1 Bottom Right) in a particular direction with the magnitude,

$$||\boldsymbol{f}|| = \begin{cases} f_p & t_0 \leq t \leq t_0 + \delta t \\ 0 & Otherwise \end{cases},$$

where $\boldsymbol{f}$ is the desired force at the reference point and f_P, t_0, and δt are the amplitude, the onset, and the duration of the impulse, respectively.

In the human study, the reference point on the end-effector was selected to be the center of the surface where the end-effector and the head make contact. The amplitude of the force was set to be 10 N. This force amplitude is equivalent to 25% of the weight of a healthy adult's head. The duration of the impulse was set to be 300 ms. This value was manually tuned so that the robot can provide a desired force amplitude.

III. Human Experiment

We investigated the applicability of this robotic brace to generate direction-specific force perturbations on the head. To this end, we carried out a human experiment with ten able-bodied participants. The individuals responded to force perturbations with eyes open or closed (*EO* or *EC*, respectively). We chose eight directions (Figure 2 Left) starting from the head in the neutral - anterior (A), anterior-right (AR), right (R), posterior-right (PR), posterior (P), posterior-left (PL), left (L), and anterior-left (AL). This experiment was approved by the Institutional Review Board (IRB) at Columbia University.

A. Subjects and Instrumentation

Ten able-bodied subjects (3 females and 7 males, Age: 28.9 ± 3.9 yr, Height: 178.1 ± 7.5 cm, Weight: 80.3 ± 14.7 kg) were recruited. Upon obtaining written consent, a subject sat during the experiment (Figure 2 Middle). Surface electromyography (sEMG) was used in this experiment (DTS, Noraxon USA Inc., Scottsdale, AZ, USA). Following skin preparation by cleaning with isopropyl pads, electrodes were bilaterally placed on two primary neck muscles: sternocleidomastoid (SCM) and splenius capitis (SPL). The robotic neck brace was aligned and then firmly attached to the user's shoulders and forehead by tightening the straps. Encoders in the servomotors recorded the joint angles of the neck brace. The head-neck

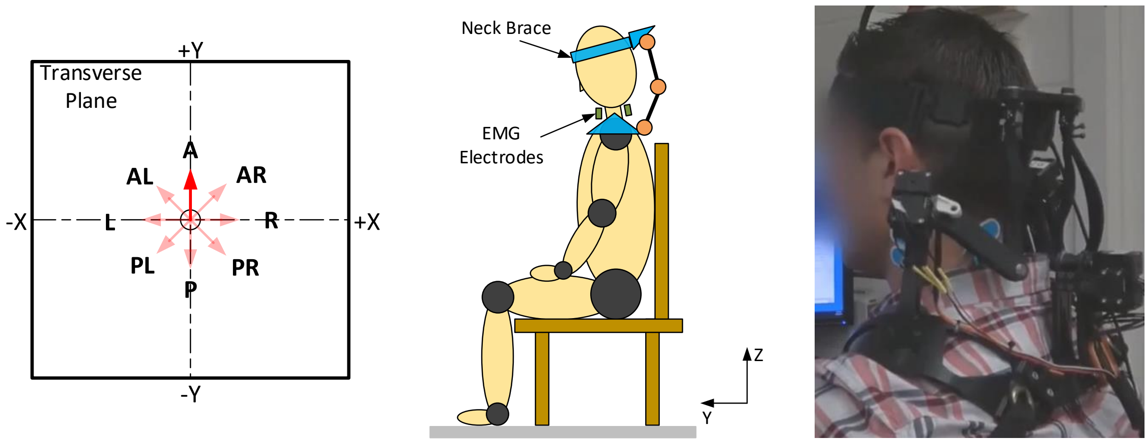

Fig. 2: (Left) Directions of eight force perturbations shown in the horizontal plane. (Middle) Schematics of the experimental setup (side view). (Right) A subject participating the experiment.

orientation was then computed by the forward kinematic model of the robot.

B. Procedures

The experiment started with a baseline recording where the subject sat upright for 60 seconds. The purpose of this baseline trial was to record the neck muscle EMG while resting.

The baseline trial was then followed by two perturbation trials. In the first trial, the eyes of the subjects were closed. In the second, the eyes were open. Each trial was 90 seconds long. An impulsive force of 10 N was applied to the head of the subject every 10 seconds in one of the eight directions. The order of these eight perturbations was randomized so that the subjects could not anticipate and pre-plan their head-neck movement. The subject was instructed to return the head back to the upright neutral after being perturbed by the force each time.

C. Data Processing

The sampling rate of the neck brace was 50 Hz. The kinematics data was low-pass filtered at 10 Hz to remove high-frequency noise. The sampling rate of the EMG was 1.5 kHz. The raw EMG signals were centered and band-pass filtered between 20 and 300 Hz, followed by a full-wave rectification.

To detect the onset/offset of sEMG, the signals were conditioned through Teague-Kaiser Energy Operation (TKEO) [15]. It was followed by a thresholding algorithm with a sliding window of 50 milliseconds.

D. Outcome Variables

1) Total Head Excursion: This is a kinematic variable which describes the accumulated displacement of the reference point on the head of the subject, recorded by the neck brace, during each perturbation in a condition (Figure 3). This variable quantifies the overall kinematic reaction and repositioning of the head-neck following a perturbation.

2) Range of Angular Displacement: This variable determines the range of rotation of the head-neck during each perturbation in a condition. The spatial rotation is decoupled into three planar rotations following Space Three 1-2-3 sequence (sagittal plane flexion-extension, coronal plane lateral bending, and transverse plane axial rotation).

3) Number of EMG Bursts: Each onset and its subsequent offset defines a muscle burst. To ensure a physiological neck muscle contraction, a muscle burst must also last for at least 80 milliseconds. A muscle burst indicates a muscle activation (Figure 3). The number of such bursts is used to quantify the overall activity of a muscle caused by a perturbation. A muscle may activate to counter-react a sudden force or to reposition the head during each 10-second perturbation segment. In the ensuing analysis on group data, we evaluate this variable in groups based on the following physiological synergy among neck muscles [13], i.e., flexors (*Flex* - left/right SCM), extensors (*Ext*- left/right SC), left lateral-flexors (*L-Latflex* - left SCM and SC), right lateral-flexors (*R-Latflex* - right SCM and SC), left rotators (*L-Rot* - right SCM and left SC), and right rotators (*R-Rot* - left SCM and right SC).

4) Integrated EMG: Integrated EMG (iEMG) quantifies the overall activity of a muscle during a finite time. We used this variable to analyze the level of activation of the neck muscles. The iEMG from a muscle was normalized against the baseline recording (resting) during 10 seconds. Therefore, the iEMG was integrated over the completion time of a subject in a condition.

E. Statistical Analysis

The statistical analysis was performed using SPSS (version 26, IBM). We applied Generalized Estimating Equations (GEEs) to analyze events-in-trials following a repeated-measures procedure. Participant data were analyzed including experimental condition (*EC* and *EO*) and perturbation directions as within-subject variables. A linear model was selected. An exchangeable covariance structure was specified as correlation matrix based on the quasi-likelihood under

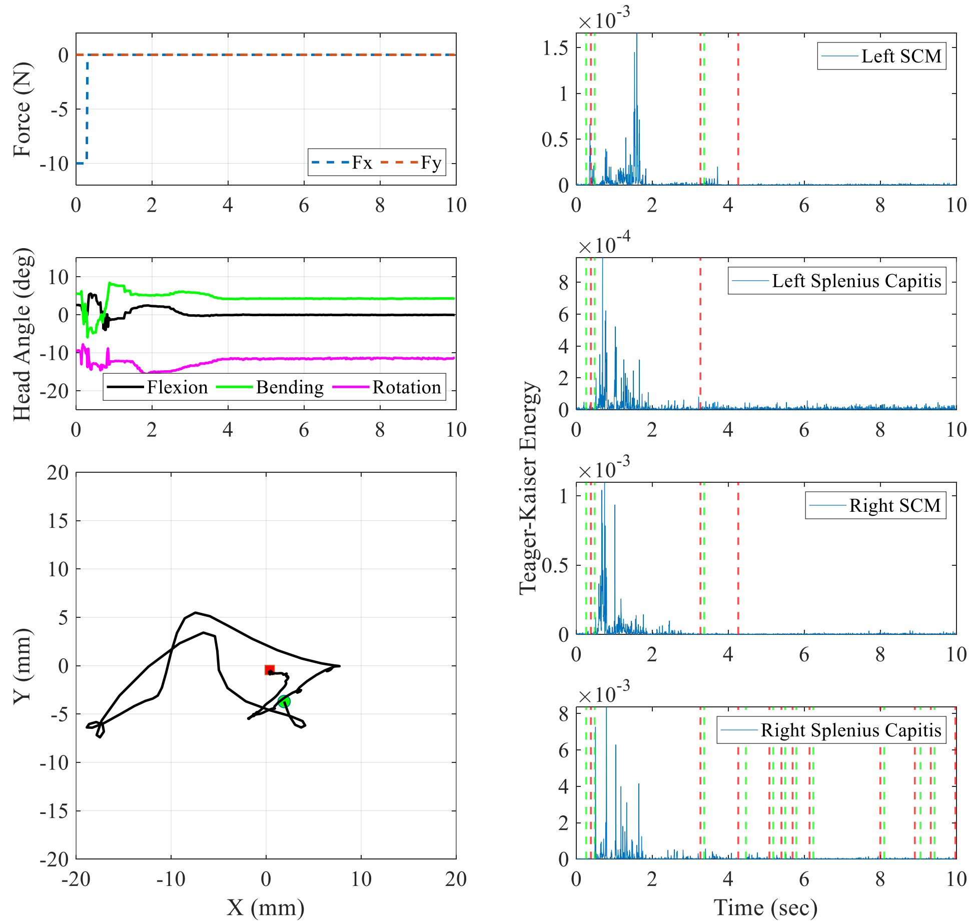

Fig. 3: Representative data of a subject during a left perturbation with eyes closed. (Top Left) Force command to the robotic brace. The force command changed instantaneously from 0 to -10 N in the x direction (left perturbation) at $t = 0$ second. This force pulse lasted 0.3 second. (Middle Left) Angular displacement of the head-neck during and after this perturbation. (Bottom Left) Trajectory (black line) of a reference point in the head, projected on the transverse plane. The green dot and the red square denote the initial and the end positions, respectively. (Right) EMG profiles after TKEO. Each muscle burst is confined between a green (onset) and a red (offset) dashed lines.

independence criterion (QIC) goodness of fit coefficient. Post-Hoc testing was carried out. In case of significance, sequential Holm-Bonferroni method was applied to correct multiple comparisons. The alpha rate was set at 0.05.

IV. RESULTS

The experimental condition had an effect on head stability, as indicated by the increase in total head excursion (Figure 4). The absence of vision increased the head excursions when the subjects received perturbations across all directions (Wald $\chi^2(1) = 9.58,\ p = 0.002$).

GEE analysis revealed that vision had a significant effect on angular head displacements during perturbations in the sagittal (Wald $\chi^2(7) = 101.11,\ p < 0.001$), frontal (Wald $\chi^2(7) = 28.35,\ p < 0.001$), and transverse (Wald $\chi^2(7) = 300.81,\ p < 0.001$) planes. Table I summarizes the mean differences of the angular head displacement between the two visual conditions (i.e., *EO* vs. *EC*) across perturbation and head-neck movement directions. For example, the mean difference in angular displacement between *EO* and *EC* in the

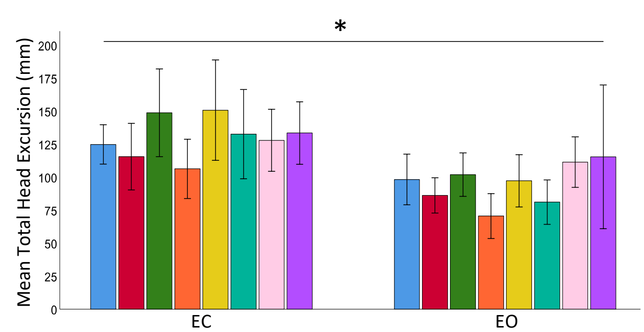

Fig. 4: Effect of vision on total head excursions across perturbation directions. The bars are color-coded based on perturbation directions, i.e., blue - anterior, red - anterior-right, green - right, orange - posterior-right, yellow - posterior, cyan - posterior-left, pink - left, purple - anterior-left ($^* = p < 0.005$).

sagittal plane is 10° when a perturbation was applied in the anterior-right direction. This value is significantly different compared to the angular displacement in the same plane but

TABLE I: Mean differences of head rotations between eyes open and closed conditions in the sagittal (flexion-extension), frontal (lateral bending), and transverse (axial rotation) planes during direction-specific perturbations. Significant main effects between paired directions are represented as Anterior = *; Anterior-Right = $^{\#}$; Right = **; Posterior-Right = $^{\#\#}$; Posterior = ***; Posterior-Left = $^{\#\#\#}$; Left = ****. Anterior-Left perturbation comparisons are redundant and not included in the table.

Perturbation Direction	Flexion-Extension (±SE)	Lateral Bending (±SE)	Axial Rotation (±SE)
Anterior	14° (±0.7)	7° (±0.5)	21° (±0.8)
Anterior-Right	10° (±0.8)*	9° (±0.6)	19° (±1.1)
Right	7° (±0.9)*	16° (±0.4)$^{*,\#}$	13° (±0.6)$^{*,\#}$
Posterior-Right	7° (±0.5)*	17° (±0.8)$^{*,\#}$	20° (±1.4)**
Posterior	14° (±0.7)$^{\#,**,\#\#}$	15° (±2.0)$^{*,\#}$	24° (±1.6)$^{\#,**}$
Posterior-Left	13° (±0.8)$^{**,\#\#}$	10° (±0.7)$^{*,**,\#\#,***}$	18° (±1.1)*,**,***
Left	9° (±0.4)$^{*,**,\#\#,***,\#\#\#}$	14° (±0.6)$^{*,\#,\#\#\#}$	11° (±1.2)$^{*,\#,\#\#,***,\#\#\#}$
Anterior-Left	9° (±0.9)$^{*,***,\#\#\#}$	14° (±1.0)$^{*,\#}$	15° (±1.1)$^{*,\#,***}$

caused by the perturbation applied in the anterior direction. This table demonstrates that the angular response of the head-neck is direction-specific.

The number of EMG bursts was significantly reduced in all muscle groups except for extensors (Mean *EC-EO* difference $= 0.9 \pm 1.0$, Wald $\chi^2(1) = 2.74$, $p = 0.098$). The number of sEMG bursts significantly increased without vision when the robotic brace delivered the perturbations in flexors (Mean *EC-EO* difference $= 0.7 \pm 0.3$, Wald $\chi^2(1) = 5.06$, $p = 0.025$); left lateral-flexors (Mean *EC-EO* difference $= 0.8 \pm 0.3$, Wald $\chi^2(1) = 8.01$, $p = 0.005$), right lateral-flexors (Mean *EC-EO* difference $= 0.7 \pm 0.4$, Wald $\chi^2(1) = 4.27$, $p = 0.039$), left rotators (Mean *EC-EO* difference $= 0.9 \pm 0.3$, Wald $\chi^2(1) = 8.55$, $p = 0.003$), and right rotators (Mean *EC-EO* difference $= 0.7 \pm 0.3$, Wald $\chi^2(1) = 5.39$, $p = 0.020$).

The level of neck muscle activity (iEMG) was not significantly different between visual conditions but dependent on perturbation direction (Figure 5). This effect was consistent across neck muscles: flexors (Wald $\chi^2(7) = 53.98$, $p < 0.001$), extensors (Wald $\chi^2(7) = 23.27$, $p = 0.002$), left lateral-flexors (Wald $\chi^2(7) = 27.98$, $p < 0.001$), right lateral-flexors (Wald $\chi^2(7) = 69.86$, $p < 0.001$), left rotators (Wald $\chi^2(7) = 84.39$, $p < 0.001$), and right rotators (Wald $\chi^2(7) = 72.90$, $p < 0.001$).

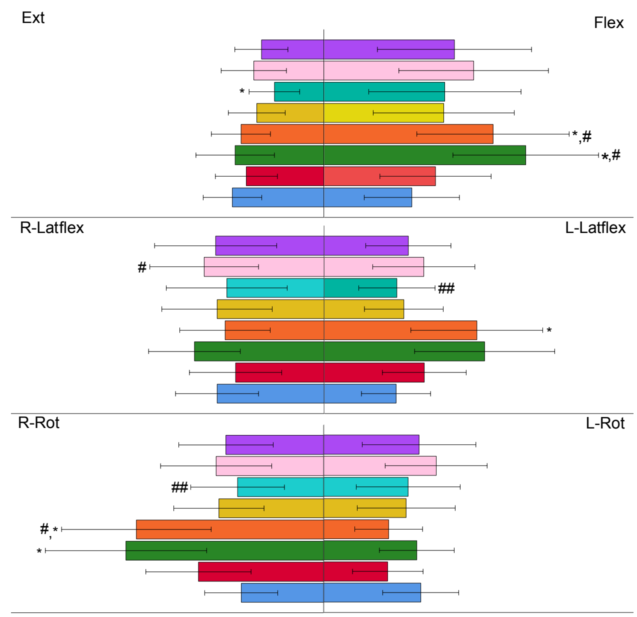

Fig. 5: iEMG of each muscle group during perturbations. The bars are color-coded and are consistent with Figure 4. The symbols showing significant main effects between paired directions are labeled following the same convention as Table I. Each bar represents the accumulated muscle response over 10 seconds, in both visual conditions, of a particular muscle group during a perturbation in one of the eight directions.

V. Discussion

Visual, auditory, and vestibular information in addition to proprioceptive signals from neck muscles are vital in postural control. The critical sensory organs that detect this information are housed in the head. There is abundant research on modulation of somatosensory, vestibular, and visual inputs and external perturbations and their influence on the neuromechanics of standing postural stance in able-bodied individuals and people with neuromotor disorders of peripheral or central origin [16], [17], [18], [19]. The ability to control the head actively and reactively in the inertial space and the trunk during standing and dynamic conditions, such as gait are crucial to build more complex postural responses. Head-neck control deficits hamper the ability to establish a postural frame of reference. This may have significant consequences for multisensory integration and ultimately in the control of posture. For instance, when the balance is highly challenged (e.g., walking on a balance beam), head control becomes a priority [20]. In perturbative environments, reflexive (vestibulocollic and cervicocollic mechanisms) and volitional head control can be highly limited [21]. Most of the experimental paradigms designed to deliver head perturbations are restricted to anterior-posterior directions. Additionally, some of the systems may require preloading of the subjects which results in inconsistent outcomes.

Our perturbation data with the use of the robotic neck brace elucidate neurophysiological reflexive head-neck-trunk control mechanisms. When vision was removed, able-bodied participants demonstrated different muscle responses to react to the unexpected perturbations. Instead of relying on vision to provide a visual reference, the subjects appeared to rely on muscle-generated proprioceptive signals and vestibular information that required trial-and-error practice to restore the position of the head. This inference is supported by the greater head excursion and the higher number of bursts of neck muscles when vision was absent. This demonstrated the ability of this robotic brace to perturb the head and monitor its kinematic responses.

The robotic head-neck brace allows investigations on kinematic and neuromuscular head-neck responses that are specific to directional perturbations. We observed that perturbations with the same amplitudes but from different directions generated different amounts of angular displacements. This underlined the asymmetric anatomic structure of the head-neck and suggested that the reactive control of the neck muscles may be direction specific. In other words, the central nervous system may prioritize certain directions over others (posterior over anterior). We also observed that the extensor group displayed direction-specific activation patterns with greater iEMG during anterior than posterior head perturbations. Research has broadly shown similar muscles responses in lower extremities (tibialis anterior and gastrocnemius) to control bipedal posture at the level of the ankle during the translation of the standing surface via moving platforms [22]. Another finding was that the participants showed greater level of activation (iEMG) in lateral flexor and rotator muscles during lateral and diagonal posterior perturbations than in anterior directions. We comprehend this observation as a reflexive protective mechanism to avoid potential injures of the bone-soft tissue structures located in posterior neck region when the head is pushed backwards.

VI. Conclusions

This paper proposes to use a robotic neck brace to apply small force perturbations on the head with two applications in mind. The first is to address current engineering limitations and conduct scientific studies. The second is to offer clinicians a more systematic and objective method to assess the head-neck control of individuals with neural impairments. The robotic system was shown to be effective to apply direction-specific perturbative forces and track different motion and muscle patterns, for instance, when the vision was removed. The portability and the ability to deliver a controllable force on the head made this robot appealing for these applications.

VII. Acknowledgment

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