



Short communication

Quantitative measures of sagittal plane head–neck control: A test–retest reliability study

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ABSTRACT

Determining the reliability of measurements used to quantify head–neck motor control is necessary before they can be used to study the effects of injury or treatment interventions. Thus, the purpose of this study was to determine the within- and between-day reliability of position tracking, position stabilization and force tracking tasks to quantify head–neck motor control. Ten asymptomatic subjects performed these tasks on two separate days. Position and force tracking tasks required subjects to track a pseudorandom square wave input signal by controlling their head–neck angular position (position tracking) or the magnitude of isometric force generated against a force sensor by the neck musculature (force tracking) in the sagittal plane. Position stabilization required subjects to maintain an upright head position while pseudorandom perturbations were applied to the upper body using a robotic platform. Within-day and between-day reliability of the frequency response curves were assessed using coefficients of multiple correlations (CMC). Root mean square error (RMSE) and mean bandpass signal energy, were computed for each task and between-day reliability was calculated using intra-class correlation coefficients (ICC). Within- and between-day CMCs for the position and force tracking tasks were all ≥ 0.96 , while CMCs for position stabilization ranged from 0.72 to 0.82. ICCs for the position and force tracking tasks were all ≥ 0.93 . For position stabilization, ICCs for RMSE and mean bandpass signal energy were 0.66 and 0.72, respectively. Measures of sagittal plane head–neck motor control using position tracking, position stabilization and force tracking tasks were demonstrated to be reliable.

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1. Introduction

Motor control of the head–neck system is commonly quantified and described in terms of task error or accuracy (Almosnino et al., 2010; Descarreaux et al., 2007, 2010; Kristjansson et al., 2001, 2003, 2004; Swait et al., 2007). Such methods have been shown to be reliable (Michiels et al., 2013), successful in detecting improvements following intervention (Beinert and Taube, 2013; Reid et al., 2014), and able to discriminate between individuals with neck pain and asymptomatic controls (Chen and Treleaven, 2013; Descarreaux et al., 2010; Woodhouse and Vasseljen, 2008). While specific metrics, such as task error in the time domain, provide

valuable information regarding subject performance, these measurements alone do not allow for inferences into system dynamics. For instance, assessing error in the frequency domain can be used to quantify the “responsiveness” of a control system at various frequencies (Cofre Lizama et al., 2013). Furthermore, frequency response data can also be used in system identification techniques to develop parametric models (Ljung, 1999), which can then be used to gain insight, for example, into specific sources of impairment in performance.

Systems-based approaches have been used to investigate the biomechanics and motor control of the human head–neck system. Such an approach typically involves the subject responding to an external stimulus (input), such as visual targets or external perturbations. For example, system identification techniques have been implemented to investigate the vestibulo-ocular reflex characteristics during a head tracking task (Tangorra et al., 2004). Additionally, the response of the head–neck system to external anterior–posterior trunk perturbations has been used to

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determine the viscoelastic properties of the head–neck system (Fard et al., 2003, 2004), to study the vestibular system characteristics (Keshner, 2003), and to assess the relative contribution of reflexes to head–neck stabilization (Forbes et al., 2013). These studies were performed on healthy subjects and did not attempt to investigate changes in motor control following injury or treatment intervention.

Before measurements of motor control can be used to detect changes in control (e.g., following injury or intervention), the test–retest reliability of the measurement must be determined. Various, systems-based measures of motor control have been shown to be reliable, including trunk control (Hendershot et al., 2012; Reeves et al., 2014) and standing balance (Cofre Lizama et al., 2013); however, we are unaware of any studies investigating the reliability of position- and force-controlled tasks of the head–neck system. Therefore, the purpose of this study was to determine the within- and between-day reliability of position tracking, position stabilization and force tracking tasks to quantify head–neck motor control (position refers to *angular* position throughout the paper).

2. Methods

The methods used in this study were based on a previous publication by our group investigating trunk motor control (Reeves et al., 2014). We have adapted the same methods to investigate head–neck motor control and the description of these methods was taken from the published material with some slight modifications.

2.1. Subjects

Ten healthy subjects (7 females) participated in the study (Table 1). Subjects were in self-reported good general health with no history of neck pain lasting longer than 3 days or neurological conditions that could affect their motor control. The research protocol was approved by the Michigan State University's Biomedical and Health Institutional Review Board and all subjects signed an informed consent form prior to participating.

2.2. Data collection

A simplified model of motor control for the head–neck system is represented in Fig. 1. Briefly, the dynamical system plant, P , is a function of the physical parameters (e.g., subject anthropometrics) and the control process, K , represents the motor control logic for ensuring desired head–neck behavior. The reference input is denoted as $r(t)$, the disturbance input (perturbation) as $d(t)$, and the system output signal is denoted as $y(t)$. The error signal is denoted as $e(t)$, where $e(t) = r(t) - y(t)$. The control objective for all tasks is to minimize the error, such that $e(t) \rightarrow 0$.

Head–neck motor control was assessed using position tracking, position stabilization, and force tracking tasks. Head position tracking and stabilization were performed using an experimental set-up that included a robotic platform (Mikrolar Rotopod R3000, Hampton, NH) (Fig. 2A). The robotic platform was only used for applying disturbances to the subject during the position stabilization task. Head and robotic platform angular positions were recorded using two pairs of string potentiometers (Celesco SP2-50, Chatsworth, CA). The experimental set-up for force tracking included a uniaxial load cell (Artech 20210, Riverside, CA) to record the force generated by neck muscles (Fig. 2B) and this task was performed separately in flexion and extension directions. A computer monitor (Samsung SyncMaster SA650; height 27 cm, width 47.5 cm), placed 1 m from the subject's eyes, displayed the reference input $r(t)$ and the output $y(t)$ signals for position and force tracking tasks, but not for position stabilization, in which the monitor was turned off so that no visual feedback regarding the reference input $r(t)$ and output $y(t)$ signals was provided.

For the tracking tasks, subjects were instructed to keep either their head position (position tracking) or force (force tracking), denoted by $y(t)$ in Fig. 2A and

Table 1

Demographic characteristics of the subjects presented as means (\pm S.D.).

	Females ($n=7$)	Males ($n=3$)
Height [m]	1.66 (0.11)	1.78 (0.07)
Weight [kg]	55.3 (11.8)	87.7 (17.7)
Age [yrs]	22.3 (1.2)	34.0 (11.8)

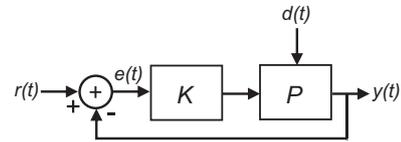


Fig. 1. Components of the head–neck motor control system. P —plant; K —control processes; $r(t)$ —reference input signal; $d(t)$ —disturbance input signal; $y(t)$ —system output signal; $e(t)$ —error signal.

B, on the time-varying reference input signal $r(t)$. Subjects performed all tracking tasks with their upper body in an upright posture (strapped to a backrest) and their arms crossed in front of their upper body. For the tracking tasks, no upper body disturbances were applied with the robotic platform (i.e., $d(t)=0$). Reference input signals $r(t)$ for the tracking tasks represented a pseudorandom square wave trajectory that varied in both hold period (0.3–0.9 s) and amplitude (Table 2). Subjects performed five trials (two 15 s practice trials and three 30 s trials) in the sagittal (flexion/extension) plane for each of the position, flexion force, and extension force tracking tasks. These parameters were determined empirically such that the reference input signal was not easily predictable, and contained a full range of frequencies within which subjects operate (system's frequency bandwidth) without being visually disturbing. For the head–neck system, this appears to be approximately up to 1 Hz (Chen et al., 2002; Peng et al., 1996).

For the position stabilization task, subjects were seated in a chair on the robotic platform in an upright posture (strapped to a backrest) and sagittal plane angular disturbances $d(t)$ were applied to the upper body (about the C7 spinal level) using the robotic platform. To ensure the robot platform rotated about the C7 spinal level, the vertical distance from the platform surface (coordinate system origin) to the subject's C7 spinous process was measured and the robot was programmed to rotate about this coordinate system offset. During the stabilization task, subjects were instructed to keep their head position upright and arms crossed in front of their body. Since a square wave trajectory could not be replicated by the robot, the disturbance input signal $d(t)$ for the stabilization task was generated from a pseudorandom sum-of-sine waves trajectory with the majority of the power spectrum ranging from 0.1 to 3.5 Hz with gradually decreasing power in higher frequencies (Mugge et al., 2007) (see Table 2 for other signal characteristics). Similar to the tracking tasks reference input signal characteristics, the disturbance input signal contained a range of frequencies to identify subjects' frequency bandwidth, which was based on preliminary data investigating the roll-off characteristics of the frequency response curve at the lower and upper ends. Subjects performed five trials (two 15 s practice trials and three 50 s full length trials) in the sagittal (flexion/extension) plane.

All data were synchronized using custom LabVIEW software and sampled at a rate of 60 samples/s using a 32-bit data acquisition system (National Instruments cDAQ-9172, Austin, TX). Testing was conducted on two different days, separated by a minimum of 24 h. Task order was kept consistent between days: (1) flexion/extension position tracking, (2) flexion/extension position stabilization, (3) flexion force tracking, and (4) extension force tracking. Rest periods (approximately 30 s) were given between all trials.

2.3. Data analysis

Root mean square error (RMSE) was used to quantify the size of the error signal $e(t)$ in the time domain. Empirical transfer function estimation and periodograms were calculated from the input signals, $r(t)$ or $d(t)$, to the output $y(t)$ and used to generate frequency response curves (Figures 3E–F and 4E–F) (Brillinger, 2001; Ljung, 1999). Mean bandpass signal energy (which will be referred to as E_{mb} for the rest of the paper) was used to assess error, $e(t)$, of the head–neck motor control system in the frequency domain. This can be expressed by the following equation:

$$E_{mb} = \frac{1}{k_h - k_l} \sum_{k=k_l}^{k_h} S_{yy}(f_k) \Delta f,$$

where $S_{yy}(f_k)$ is the value of the discrete error signal power spectrum (deg^2/Hz for position tracking and stabilization tasks or N^2/Hz for force tracking tasks) at equally spaced discrete frequencies f_k (Hz), Δf is the difference between two subsequent frequencies in the power spectrum, k_l is the frequency index value corresponding to the lower bound of the passband (f_{k_l}), and k_h is the frequency index value corresponding to the upper bound of the passband (f_{k_h}).

The E_{mb} was computed over passband regions defined from preliminary data as the contiguous frequency band containing $> 3\%$ of the maximum power of the input signal ($r(t)$ or $d(t)$) and was greater than or equal to 0.1 Hz. These criteria were selected to maximize the reliability for each task. Therefore, the passband regions were 0.1–1.66 Hz for the tracking tasks and 0.5–2.9 Hz for position stabilization, and E_{mb} represented a measure of the mean error signal energy over the defined passband regions.

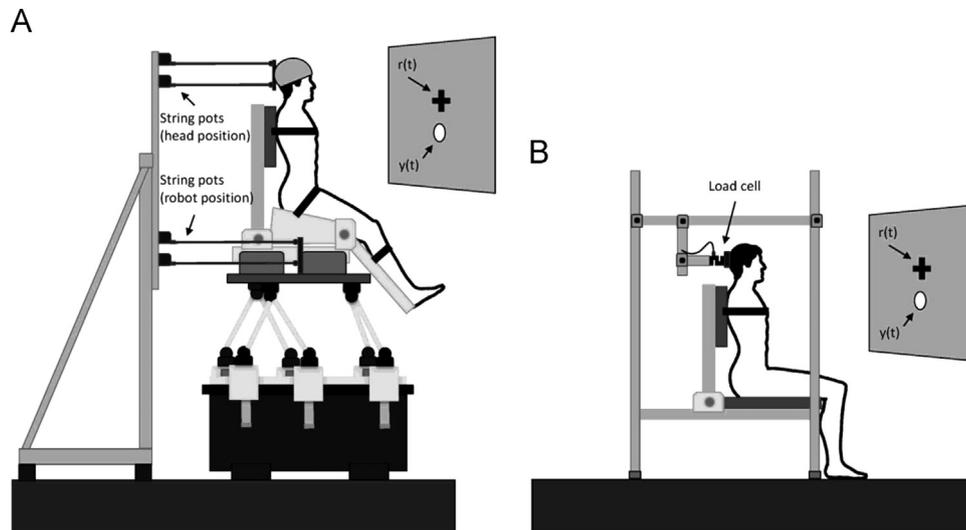


Fig. 2. Experimental set-up for (A) position tracking and stabilization and (B) force tracking. Visual feedback was provided from a monitor placed 1 m in front of the subject. For tracking tasks, the reference input signal $r(t)$ varied within a range equal to 60% of the full screen height, centered around the middle of the screen.

Table 2
Characteristics of input signals for the head–neck motor control tasks.

Task	$d(t)$ Amplitude	$r(t)$ Amplitude
Position tracking	0°	$\pm 4^\circ$ Centered around 0° ^a
Force tracking	0°	$\pm 3\%$ Centered around 5% ^b
Position stabilization	$\pm 2^\circ$ Centered around 0° ^a	0°

^a 0° represents an upright head–neck position. For the disturbance input signal $d(t)$, the robot was programmed to apply pure rotations about a subject's C7 spine level that was bounded by $\pm 2^\circ$ (see Fig. 4C).

^b For force tracking, the level of force exerted on the load cell was derived from maximum strength estimates in the literature (Jordan et al., 1999; Salo et al., 2006; Strimpakos et al., 2004; Vasavada et al., 2008; Vasavada et al., 2001), expressed in Nm about the C7 spinal level. For males, the maximum strength was assumed to be 30 Nm in flexion and 50 Nm in extension. For females, the maximum strength was assumed to be 18 Nm in flexion and 30 Nm in extension. The distance from C7 to the load cell was used to convert moment effort to force effort.

Within- and between-day reliability of the frequency response curves was quantified using coefficient of multiple correlations (CMC), modified from Kadaba et al. (1989), such that the 3-dimensional space (complex domain and frequency domain) of the frequency response curves replaced the role of time-series curves. A repeated measures ANOVA was used to analyze between-day differences in RMSE and E_{mb} , with an alpha level set at $p \leq 0.05$. Intra-class correlation coefficients (ICC (3,k)) and 95% confidence intervals (CI) were used to quantify RMSE and E_{mb} between-day reliability, using the mean of three trials. The standard error of measurement (SEM) was also calculated as $SEM = SD\sqrt{1-ICC}$, which represents variability of the measurement error (Portney and Watkins, 1993). The criteria from Cicchetti (1994) were used to classify the ICCs as fair (0.40–0.59), good (0.60–0.74) or excellent (0.75–1.00).

3. Results

CMCs, quantifying the within-day and between-day reproducibility of the frequency response curves, ranged from 0.72 to 0.97 for all tasks (Table 3). RMSE and E_{mb} performance values were slightly better on the second day, suggestive of learning, although these differences were not statistically significant (Table 4). The between-day reliability values for RMSE and E_{mb} (Table 5) were excellent for all tasks ($ICC \geq 0.93$), with the exception of the position stabilization task, which was good for both RMSE ($ICC = 0.73$) and E_{mb} ($ICC = 0.66$).

4. Discussion

Determining the reliability of measurements used to quantify motor control is necessary when repeated measurements are taken

(e.g., before and after interventions). The results of this study indicate that a systems-based approach to analyzing position tracking and stabilization, and force tracking tasks produced reliable measurements for quantifying head–neck motor control in healthy subjects. This approach allows for quantification of subject performance using mean values of non-parametric measures (e.g., RMSE, E_{mb}) and provides the ability to investigate the dynamics of the system using the frequency response curves.

Accuracy, or error, of controlling the head–neck system during dynamic position tracking tasks has been previously shown to have fair–excellent between-day reliability ($ICCs = 0.53–0.97$) (Kristjansson and Oddsdottir, 2010; Swait et al., 2007). Thus, the reliability ranges of the RMSE and E_{mb} metrics used in the present study ($ICCs = 0.66–0.99$) are similar to those ranges reported previously. However, while non-parametric metrics such as RMSE and E_{mb} provide valuable information regarding subject performance, the frequency response curves contain all of the necessary information needed to understand the head–neck system dynamic behavior. Between-day reliability of those curves (CMCs) ranged from 0.72 to 0.97.

In order to interpret the frequency response of the system, the input signal trajectory characteristics should excite the system over the frequency bandwidth in which the systems operates (Kearney and Hunter, 1990). It is unlikely that the fixed and variable velocity trajectories, such as those implemented by Swait et al. (2007), covered a wide enough frequency spectrum. Similarly, while Kristjansson and Oddsdottir (2010) implemented several levels of difficulty (easy, medium and difficult lasting 25, 40 and 50 s, respectively) for their

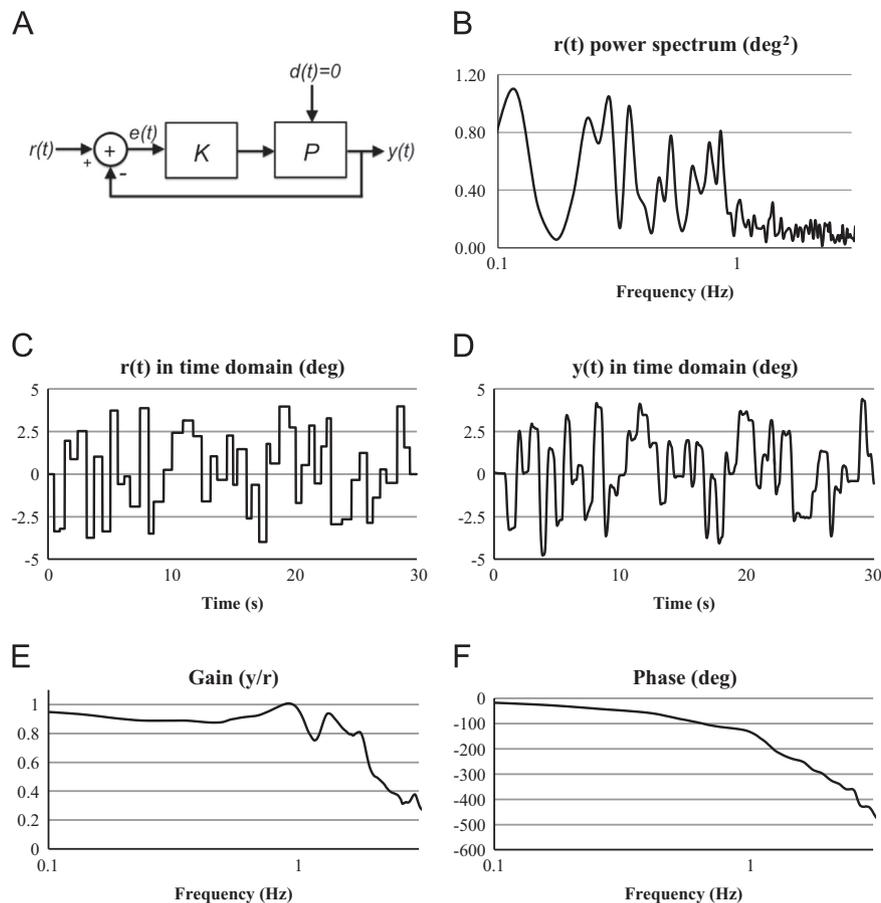


Fig. 3. Frequency response for a position tracking trial. (A) Input–output model for the head–neck motor control system. (B) Power spectrum of the reference input signal $r(t)$. (C) Pseudorandom square wave reference input signal $r(t)$. (D) Output signal $y(t)$, recorded from head position. Time series data (panels C–D) are converted to the frequency domain (panels E–F). (E) Gain and (F) phase angle characterizes the control system's ability to track the reference input signal $r(t)$. A gain of 1 and a phase angle of 0 across all frequencies represent perfect tracking. Phase angle represents the delays in the control system's response to the reference input signal $r(t)$, expressed as $\theta = 360fT$, where f is frequency and T is delay. *Note—frequency data in panels B, E and F are plotted using a log scale on the x -axis.

head–neck tracking task, it is difficult to determine whether these trajectories would allow for investigation of system dynamics over the system's entire frequency bandwidth, which is approximately up to 1 Hz (Chen et al., 2002; Peng et al., 1996). The input signals used in the current study were designed to be unpredictable (pseudorandom), achievable without causing visual disturbances, and able to excite the head–neck system across the system's frequency bandwidth. This approach is advantageous because it provides us with complete information about the control of the head–neck system over the entire operating range of frequencies. Thus, with our method, changes in the system's bandwidth or changes in the system's performance in the specific range of frequencies can be determined.

Our findings are consistent with a previous study conducted by our group (Reeves et al., 2014) that used similar tasks and input signal characteristics for assessing trunk motor control. We observed similar trends to the Reeves et al. (2014) study in which tracking tasks were shown to be more reproducible than a position stabilization task. It is difficult to make the direct comparison between these two types of tasks because of differences in the input signal characteristics (Figs. 3 and 4), the goals of the tasks (tracking versus stabilization) and visual feedback (monitor turned off during stabilization); however, for position stabilization, the lower signal-to-noise ratio (see means and S.D. in Table 4) may have reduced within- and between-day reliability. Additionally, the lower within-day CMC for the stabilization task suggests there is greater variability in this task performance, which would affect reliability.

The improvement in RMSE and E_{mb} performance values between days suggests there may have been learning taking place. Subjects

were given two practice trials to become familiar with the tasks and to minimize the effect of learning. We also used the mean of three trials to calculate the reliability (ICCs) of the non-parametric performance metrics to provide better estimation accuracy, which is commonly used in biomechanics. Additional practice trials could allow similar reliability to be obtained with fewer replications.

There are some limitations to our study worth mentioning. Most notably, while there was a minimum of 24-h between test days, we did not control for the amount of time between test sessions (ranged from 24 to 45 h). We also did not monitor or control for activities that may have influenced performance of the tasks over this time period. Additionally, the task order was not randomized, but was standardized to minimize participant testing time and limit the influence of fatigue as we plan to implement this type of testing on patients with neck pain in the future. By standardizing task order, the effects of testing order on reliability were minimized. However, it is possible that by standardizing the task order, subjects could have performed better on the later tracking tasks (force tracking), which resulted in the highest reliability. Despite these limitations, the tasks used to quantify motor control of the head–neck system demonstrated good to excellent reliability in this small population of healthy participants. It should be noted that due to the small sample size and population tested, these results may not be generalizable to other populations.

In conclusion, the results of the present study indicate that mean time domain and frequency domain measures of head–neck control are reliable with position and force tracking tasks being more reliable than the position stabilization task. Future studies will focus on applying these systems-based techniques to quantify

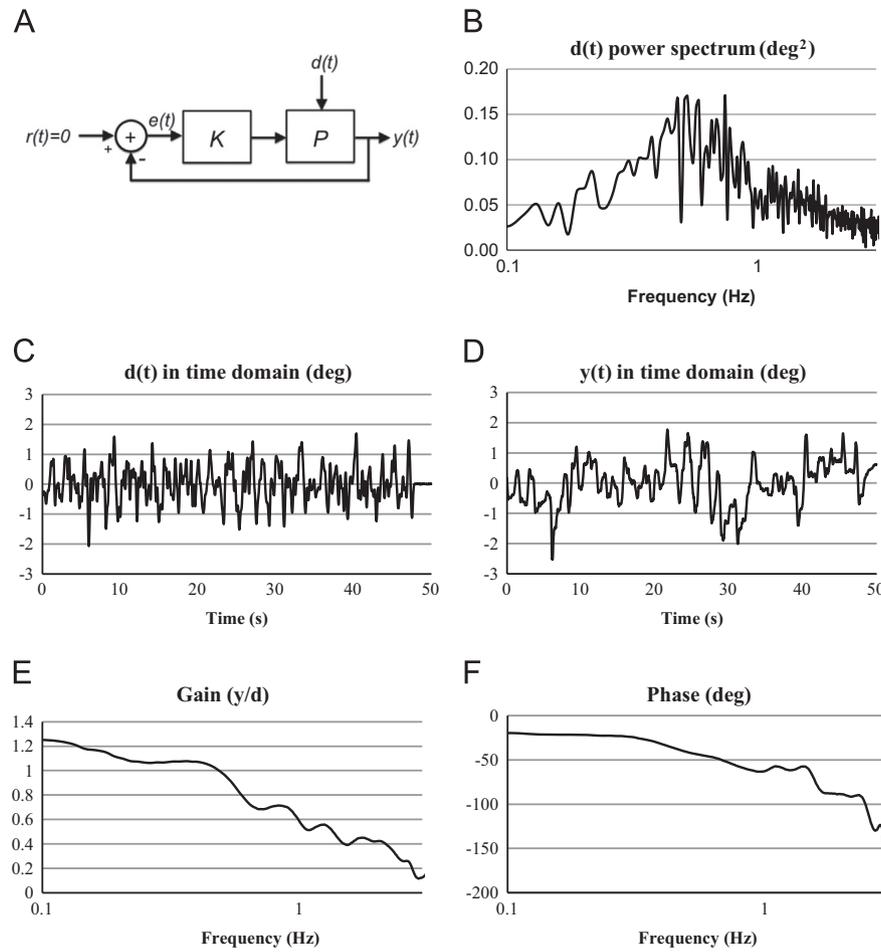


Fig. 4. Frequency response for a position stabilization trial. (A) Input–output model for the head–neck motor control system. (B) Power spectrum of the disturbance input signal $d(t)$. (C) Time–series presentation of the pseudorandom sum-of-sine waves disturbance input signal $d(t)$. (D) Output signal $y(t)$, recorded from head position. Time series data (panels C–D) are converted to the frequency domain (panels E–F). (E) Gain and (F) phase angle characterizes the control system’s ability to reject the disturbance input signal $d(t)$. A gain of 0 and a phase angle of 0 across all frequencies represent perfect tracking. Phase angle represents the delays in the control system’s response to the disturbance input signal $d(t)$, expressed as $\theta=360fT$, where f is frequency and T is delay. *Note—frequency data in panels B, E and F are plotted using a log scale on the x-axis.

Table 3
Within-day and between-day frequency response curve reproducibility. Data presented as CMC (95% CI).

Task	Within-day CMC	Between-day CMC
Flexion/extension position tracking	0.97 (CI 0.96–0.98)	0.97 (CI 0.96–0.98)
Flexion/extension position stabilization	0.82 (CI 0.73–0.90)	0.72 (CI 0.62–0.82)
Flexion force tracking	0.97 (CI 0.95–0.98)	0.96 (CI 0.95–0.97)
Extension force tracking	0.97 (CI 0.96–0.98)	0.97 (CI 0.96–0.98)

Table 4
RMSE and E_{mb} performance values during the various motor control tasks. Data presented as mean (\pm S.D.).

Task	RMSE		P-value	E_{mb}		P-value
	Day 1	Day 2		Day 1	Day 2	
Flexion/extension position tracking	2.62 deg (0.13)	2.60 deg (0.10)	0.37	114.88 deg ² (13.89) ^a	113.17 deg ² (10.48) ^a	0.39
Flexion/extension position stabilization	0.94 deg (0.27)	0.84 deg (0.20)	0.18	0.91 deg ² (0.48) ^a	0.80 deg ² (0.25) ^a	0.37
Flexion force tracking	2.59 N (0.49)	2.53 N (0.52)	0.07	112.72 N ² (39.51) ^a	108.21 N ² (41.50) ^a	0.07
Extension force tracking	5.18 N (0.96)	5.15 N (0.99)	0.53	452.25 N ² (159.28) ^a	447.41 N ² (169.43) ^a	0.66

^a Values were multiplied by 10³.

Table 5
Between-day reliability for RMSE and E_{mb} . Data presented as ICC(3,k) (95% CI; SEM).

Task	RMSE	E_{mb}
Flexion/extension position tracking	0.93 (CI 0.72–0.98; SEM 0.03 deg)	0.94 (CI 0.74–0.98; SEM < 0.01 deg ²)
Flexion/extension position stabilization	0.73 (CI 0.08–0.93; SEM 0.12 deg)	0.66 (CI 0.39–0.91; SEM < 0.01 deg ²)
Flexion force tracking	0.99 (CI 0.97–1.00; SEM 0.04 N)	0.99 (CI 0.97–1.00; SEM < 0.01 N ²)
Extension force tracking	0.99 (CI 0.97–1.00; SEM 0.09 N)	0.99 (CI 0.96–1.00; SEM 0.02 N ²)

differences in motor control associated with neck pain and to gain insight into the head–neck system using parametric modeling.

Conflict of interest

None of the authors of this manuscript have any conflicts of interest to disclose.

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