Journal of Biomechanics 48 (2015) 549–554

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

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

John M. Popovich Jr.[a,b,*], N. Peter Reeves[a,b], M. Cody Priess[a,c], Jacek Cholewicki[a,b], Jongeun Choi[a,c,d], Clark J. Radcliffe[a,b,c]

[a] MSU Center for Orthopedic Research, College of Osteopathic Medicine, Michigan State University, Lansing, MI, USA
[b] Department of Osteopathic Surgical Specialties, College of Osteopathic Medicine, Michigan State University, East Lansing, MI, USA
[c] Department of Mechanical Engineering, College of Engineering, Michigan State University, East Lansing, MI, USA
[d] Department of Electrical and Computer Engineering, College of Engineering, Michigan State University, East Lansing, MI, USA

ARTICLE INFO

Article history:
Accepted 17 November 2014

Keywords:
Position tracking
Force tracking
Position stabilization
System identification
Cervical spine

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.

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

* Correspondence to: MSU Center for Orthopedic Research, Osteopathic Surgical Specialties, College of Osteopathic Medicine, Michigan State University, 2727 S. Pennsylvania Avenue, Lansing, MI 48910.
Tel.: +1 517 975 3318; fax: +1 517 975 3305.
E-mail address: popovi16@msu.edu (J.M. Popovich Jr.).

http://dx.doi.org/10.1016/j.jbiomech.2014.11.023
0021-9290/

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 (± 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)

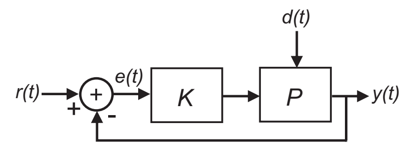

Fig. 1. Components of the head–neck motor control system. P—plant; K—control processes; $r(t)$—reference input signal; $d(t)$—disturbance input signal; $y(t)$—system output signal; $e(t)$—error signal.

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.