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COORDINATION OF THE HEAD WITH RESPECT TO THE TRUNK AND PELVIS IN THE ROLL AND PITCH PLANES DURING QUIET STANCE

F. HONEGGER, G. J. van SPIJKER AND J. H. J. ALLUM *

Department of ORL, University Hospital Basel, Basel, Switzerland

Abstract—This study examined the relationship between head and trunk sway during quiet stance and compared this relationship with that of the pelvis to the trunk. Sixteen younger and 14 elderly subjects participated, performing four different sensory tasks: standing quietly on a firm or foam support surface, with eyes open or closed. Roll and pitch angular velocities were recorded with six body-worn gyroscopes; a set of two mounted at the upper trunk, an identical set at the hips, and another set on a head band. Angle correlation analysis was performed in three frequency bands: below 0.7 Hz (LP), above 3 Hz (HP) and in between (BP) using the integrated angle velocity signals. Angular velocities were spectrally analysed.

Greater head than trunk motion was observed in angle correlations, power spectral density (PSD) ratios, and transfer functions (TFs). Head on trunk motion could be divided for all sensory conditions into a low-frequency (<0.7 Hz) "head locked to trunk" inverted pendulum mode, a mid-frequency (ca. 3 Hz), resonant mode, and a slightly anti-phasic head motion on stabilized trunk, high-frequency (>3 Hz) mode. There was coherent motion between head and trunk but not between head and pelvis. Trunk and pelvis data was consistent with previously reported in-phase and anti-phase movements between these segments. Significant age differences were not found.

This data indicates that during quiet stance body motion increases in order of pelvis, trunk, head and quiet stance involves control of at least two separate links: trunk on pelvis and head on trunk dominated by head resonance. The head is locked to the trunk for low frequency motion possibly because motion is just supra-vestibular threshold. The head is not stabilised in space during stance, rather the pelvis is. © 2012 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: balance control, multi-segmental movement strategies, vestibular signals, head resonance.

INTRODUCTION

The central nervous system (CNS) employs information from the vestibular, visual and somatosensory systems to control upright stance. These signals originate in a number of different body segments. Thus if there is relative movement between body segments the interpretation of these signals by the CNS is more complex than if there is no relative motion. For example, for the conditions of perturbed stance where body motion is multi-link, the proportion of these inputs to balance control may vary (Allum and Honegger, 1998; Allum et al., 2008; Black et al., 1983; Peterka and Loughlin, 2004). Likewise for unperturbed stance, the relative motion between the upper and lower body segments may vary with an in-phase, inverted pendulum like mode, observed at low frequencies, anti-phasic motion at high frequencies above 3 Hz (Creath et al., 2005; Horlings et al., 2009). Therefore, even the control of quiet stance is more complex than just control of an inverted pendulum. To reduce the sensory complexity this bimodal mode implies it has been suggested that lower body motion is controlled by changing the weighting of sensory inputs as sway amplitudes increases and the upper body motion is predominantly influenced by intrinsic musculo-skeletal mechanisms (Goodworth and Peterka, 2012). This may not prove a sufficient reduction in the complexity for controlling quiet stance as motion of the head needs to be taken into account.

Koozekanani et al. (1983) concluded that considering ankle movements and hip joint motion is crucial for describing balance control during quiet stance. More recently, others have shown that a single segment model (the inverted pendulum model) does not adequately represent control of upright stance; it appears that ankle, hip (or lumbo-sacral) strategies exist simultaneously (Creath et al., 2005; Horlings et al., 2009; Hsu et al., 2007; Kuo, 1995; Pinter et al., 2008), depending on the sway frequency band considered, and the type of surface (firm or foam) on which the subject is standing (Creath et al., 2005; Horlings et al., 2009), the direction (roll or pitch) of sway (Creath et al., 2005; Horlings et al., 2009), and the presence of vestibular or lower leg proprioceptive inputs (Horlings et al., 2009). Missing from these studies is information about how head movements are coordinated within these upper and lower body strategies during quiet stance.

Knowledge about head movements during stance is of interest, as head movements need to be compensated with oppositely directed eyes movement to stabilize gaze for adequate fixation on the environment. Further, the vestibular system is situated in the inner ear and receives

*Corresponding author. Address: Department of ORL, University Hospital Basel, Petersgraben 4, CH-4031 Basel, Switzerland. Tel: +41-61-265-2040; fax: +41-61-265-2750.

E-mail address: jallum@uhbs.ch (J. H. J. Allum).

Abbreviations: BP, band pass; CoM, centre of mass; CNS, central nervous system; EC, eyes closed; ECF, eyes closed on foam; EO, eyes open; EOF, eyes open on foam; gm, grand mean; HP, high pass; LP, low pass; PSD, power spectral densities; TF, transfer function.

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input whenever the head is moved. The sensory signal thereby produced can elicit eye movement or muscles counteraction to control posture, provided relative motion between body segments is known. Concerning this relative motion there are two well-known theories: the head is fixed in space or the head is stabilized on the trunk (Horak and Nashner, 1986). When upright stance is controlled in the first manner, the head is held still, that is servo-referenced to the visual input and the vestibular system output is nulled out. This mode of control has also been observed for various locomotor tasks in humans (Pozzo et al., 1990). Based on the alternative theory, head stabilized on the trunk, the head moves with the body and the vestibular system provides a measure of trunk motion. Both of these modes are highly dependent on the sensory information available and thus should be altered with changes in sensory inputs, for example, by eyes closure or reducing ankle proprioceptive input effectiveness with a foam support surface, particularly if lower body movements are controlled by proprioceptive inputs (Keshner and Kenyon, 2000). If as suggested by Goodworth and Peterka (2012) upper body motions is mostly controlled by intrinsic biomechanics, and not as supposed by vestibular inputs (Keshner and Kenyon, 2000), vestibulo-spinal reflexes would then act only to stabilise the head on the trunk by damping its biomechanical resonance (Keshner et al., 1995; Peterson et al., 2001; Goldberg and Cullen, 2011).

Several studies have suggested that the head resonates at 3 Hz when the body is perturbed. For example, a sudden pitch rotation of the surface on which subjects are standing leads to 3 Hz head oscillations (Keshner et al., 1987). Whole body rotations in the yaw plane also yield 3 Hz (Keshner and Peterson, 1995). Finally directly applied head oscillations in the pitch revealed a resonance at 3 Hz (Viviani and Berthoz, 1975). Given this evidence, it would not be surprising to observe a 3 Hz resonance of the head during quiet stance.

There has been some research about head movements during quiet stance. Karlberg and Magnusson (1998) investigated the effect of wearing a neck collar for patients with compensated unilateral peripheral vestibular loss, assuming that the collar would stabilize the head with respect to the trunk. Instead, the neck collar impaired balance in these patients. This finding suggests that head movements independent of shoulder movements are essential for maintaining postural stability. The question arises how much motion is necessary. For example, there is a tendency for head movement to be less than trunk movements when the support is oscillated (Vaugoyeau et al., 2008). As a simultaneous reduction in CoM movements occurred too, the head movements may act to counter the movements of masses having the greatest effect on CoM sway, such as the trunk and pelvis (Corna et al., 1999; Akram et al., 2008).

In this study we measured body movements at the level of pelvis, upper trunk and head in order to gain more insights into how the head moves with respect to the trunk and pelvis in order to maintain balance during quiet stance. We asked the following questions: What is the relationship between head and trunk movements of the body during quiet stance? Are head movements highly correlated with the trunk or the pelvis movements? Is an independent head resonance observed? Are the head movements with respect to the trunk different in the roll and pitch plane? Further, are head movements with respect to the trunk altered under different sensory conditions? These questions build on our previous study on the relationship between trunk and pelvis motion during quiet stance in healthy controls and those with vestibular or lower leg proprioceptive loss (Horlings et al., 2009).

In general, it is known that elderly are less flexible and have more body sway after 65 years of age (Gill et al., 2001; Nardone et al., 2000). Furthermore, healthy older adults generate more head sway than healthy young adults while performing virtual reality tasks in quiet stance (Borger et al., 1999; Loughlin and Redfern, 2001; Sparto et al., 2006; Sundermier et al., 1996), suggesting that older adults rely more on visual cues than young adults and are therefore more unstable with greater head sway. Based on this finding it is reasonable to assume that head with respect to trunk movement strategies are different between young and elderly. Here we also explored if elderly have a different relationship in body sway of the different segments compared to the younger. We found few significant differences and therefore this report concentrated on strategies of the young.

EXPERIMENTAL PROCEDURES

Subjects

Thirty healthy subjects participated in this study: 16 younger (8 F, 8 M aged 22.6 ± 3.1 (mean ± SD)) and 14 elderly (6 F, 8 M aged 68.4 ± 4.5 (mean ± SD)). The latter were recruited at a health club for the elderly in Basel, Switzerland. Subjects had no neurological, vestibular, visual, or orthopaedic problems that could influence balance, and had a body mass index (BMI) in the range of 18-30. All subjects gave witnessed, written informed, consent to participate in the experiments according to the Declaration of Helsinki. The Institutional Ethical Review Board of the University Hospital Basel approved the study.

Procedure

The subjects were asked to stand as quiet as possible during the four stance tasks: standing on both legs on a firm or a foam (F) support surface, with eyes open (EO) and closed (EC). The order of the surface used first was randomised. The block of foam used had a height, width, and length of 10 by 44 by 204 cm, and a density of 25 kg/m^3. The subjects stood without shoes, so different shoe types could not interfere with the measurements. The feet were placed at shoulder width apart and the arms were hanging at the sides of their body. While performing the eyes open tasks, subjects were asked to fixate a point 5 m away. A spotter stood next to the subject, to assist in case balance was lost. Subjects performed each task once, for 180 s. During three trials there was a technical failure in data collection, requiring data to be cut at 97 s (one young subject for ECF), and at 120 s and 150 s (both elderly subjects for EOF).

Measurement systems

Two identical gyroscope-based measurement systems of weight 500 g (SwayStar, Balance International Innovations GmbH,