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Published in:
IEEE Engineering in Medicine and Biology Magazine

2003

[Link to publication](#)

Citation for published version (APA):

Fransson, P.-A., Johansson, R., Tjernström, F., & Magnusson, M. (2003). Adaptation to Vibratory Perturbations in Postural Control. *IEEE Engineering in Medicine and Biology Magazine*, 22(2), 53-57.
<http://ieeexplore.ieee.org/iel5/51/26895/01195696.pdf>

Total number of authors:
4

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Adaptation to Vibratory Perturbations in Postural Control

There Are Several Modes of Adaptation to Postural Perturbations Used to Withstand Balance Disturbances and Reduce the Effects of Muscle Fatigue

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Adaptation and habituation are common in biological systems for movement control [1], and the ability to adjust postural control performance is of major importance during many human activities [2], [3]. Postural control uses sensory information from the visual, vestibular, and somatosensory receptors in order to detect and control the movements and coordinate voluntary and reflexive muscle responses while maintaining stability [4], [5]. The organization and coordination of the mechanical body motions have been extensively studied from the perspectives of biomechanical, neurological, and control system analysis [6]–[10]. However, the dynamical coupling between body segments, where action of one segment will affect the motions of other parts of the body, is difficult to analyze both theoretically and experimentally. The postural movements are restricted by the muscular and skeletal organization and by the geometrical configuration of the body consisting of segments moving in an interrelated fashion to each other. The ability to generate motions of the body segments are also related to the requirements of muscle force and restricted by the flexibility in the muscles, joints, and tendons [4], [11], [12].

The possibility that adaptation and muscle fatigue may lead to multimuscle and multijoint coordination changes, and reorganization of movements, has received little attention in previous studies. The regulation of the orthograde posture constitutes an essential topic of motor control not only to maintain the static posture but also to ensure body stability during various locomotory movements [13]. It is well known that the CNS employs both feedforward (predictive) and feedback (reactive) control to compensate for the perturbations that might occur during movement. Appropriate feedforward compensations, based on an adaptive internal model of the system and the expected external conditions, can greatly reduce the magnitude of required reactive responses [15]. The adaptive adjustments by the CNS during the execution of a postural task to reduce the likelihood of balance loss is of particular relevance to fall prevention [15], [16].

A recent development in posturography analysis is the use of system identification to describe the feedforward and feedback properties of the postural control system [4], [7], [8]. To assess dynamic feedback control by system identification methods, a stimulus is required that has its primary effect on a sensory input and can be applied in a well-defined manner

[17]. Vibration can be applied in a wide range of amplitudes and frequencies according to a pseudorandom binary sequence (PRBS) schedule as used in system identification [17]. Vibration applied to a muscle or a muscle tendon increases the firing of the muscle spindles, thus signaling that the muscle is being stretched [18]. The stimulated muscle responds to this with a reflexive contraction (tonic vibratory reflex) [19]. Vibration of the gastrocnemius muscles induces a movement backward whereas vibration of the paravertebral neck muscles induces a movement forward [20], [21]. Acquisition of motor skills is typically a gradual process requiring many repetitions over a period of time [22], and several reports have shown that the body movements induced during repeated exposure to postural disturbances are gradually reduced [6], [23], [24]. In this article we summarize experimental results, which demonstrate that there are several modes of adaptation to postural perturbations, and we discuss the properties of these adaptive processes.

Experimental Methods

Subjects

The tests were performed on 12 subjects (six men and six women; mean age 26 years, range 15–32 years). The subjects had no history of vertigo, central nervous disease, or injury to the lower extremities. At the time of the investigation, no subject was on any form of medication or had consumed alcoholic beverages in the previous 24 hours. Informed written consent was obtained from all subjects. The experiments were performed in accordance with the Helsinki declaration of 1975 and approved by the local ethical committee.

Methods

Postural control was evaluated by perturbing stance while the test subjects stood on a force platform (400 × 400 × 75 mm) equipped with strain-gauge sensors. Forces and torques actuated by the feet were recorded with six degrees of freedom by a force platform and sampled at 10 Hz by a computer equipped with an analog/digital converter. Perturbations mainly causing anteroposterior postural disturbances were invoked by vibratory stimuli simultaneously applied toward the right and left gastrocnemius muscles [21]. The test subjects were exposed to vibration at 1.0-mm amplitude at a constant frequency of 85 Hz turned on and off according to a PRBS

Adaptation to a novel postural challenge causes the generation of a modified motion strategy, reflected by both quantitative and qualitative alterations of the body sway responses.

(pseudo-random binary sequence) schedule [17] with pulses between 0.8 and 6.4 seconds for a duration of 205 seconds. The stimulation period was preceded by 30 seconds recording time of unperturbed quiet stance.

Procedure

The subjects were tested for five consecutive days. Two tests, one with eyes open and the second with eyes closed, were performed at approximately the same time (± 1 hour) every day. After brief information about the test procedure, the subjects were equipped with vibrators on both gastrocnemius muscles and placed on the force plate where headphones relaying music were attached. The subjects were instructed to stand erect but not at attention, with arms crossed over the chest and feet at an angle of about 30 degrees open to the front. They were told to focus on a mark placed 1.5 m straight ahead of them on the wall, or to stand with their eyes closed. The subjects stepped down from the force platform and relaxed for three minutes between the trials.

Data Analysis

The variance of body sway during the five days was obtained for five periods during the test: the quiet stance period (0-30 seconds) before stimulation was applied, and from four periods (1-4) during the stimulation (30-80, 80-130, 130-180, and 180-230 seconds, respectively). By using regression, the

torque variance values were found to be dependent on the squared height and squared weight of the subjects. The torque variance values were therefore normalized by dividing the values by the subject's squared height and weight, and, for representation purposes, multiplied by 1,000.

The measured anteroposterior torque during vibratory stimulation was also analyzed with a method that considered the adaptation of postural control. The adaptation analysis method, where the adaptation of posture as well as the adjustments of the stimulation responses during the trial are quantified by iteratively estimated nonlinear functions, is described in detail elsewhere [25].

Results

The properties of the adaptive adjustments during the posturographic test suggest that several partly independent adaptive processes are involved in the formation of new motor programs that are better able to consider and suppress the perturbations induced by the vibratory proprioceptive stimulation (Figure 1). One adaptive process can be seen in the progressive reduction of body sway induced by the individual vibratory perturbations during the test. The body sway responses to the vibratory perturbations are primarily reduced during the initial 100-120 seconds of stimulation, which contained 25-35 perturbations in our particular sequence. An additional slower adaptive process adjusts the body posture and center of pressure position. In response to vibratory stimulation applied to the gastrocnemius muscles, the test subject had initially a tendency to lean backward (positive values) but selects after a while a more forward position and maintains this position throughout the remaining test. The red line illustrates the predicted response data from an analysis method that is designed to consider the effects of the above described adaptation processes [25]. The high accuracy between the model simulation values and recorded body sway suggests that this method might be applicable to quantify the adaptive changes in posturographic recordings.

The body sway during quiet stance has a circular shaped distribution (Figure 2). The distribution of the body sway increased primarily in the anteroposterior direction but also in

Fig. 1. The top graph shows the pseudorandomized vibratory stimulation applied to the gastrocnemius muscles. The bottom graph shows measured anteroposterior torque (green) from a normal test subject exposed to vibration with eyes closed and the model simulation values (red). Note the changes in sway amplitude and body position over time after the stimulation onset.

Perturbations evoked by vibratory stimulations induce simultaneous body movements in all body segments, corresponding to an approximate single-link pendulum pattern.

the lateral direction during vibratory stimulation of the gastrocnemius muscles. The elliptic distribution profile of the body sway is largely maintained over time even though the average center point of pressure position and body sway amplitudes are altered.

In addition to the two adaptive processes active during the trial (Figure 1 and Figure 2), a third more long-term adaptive process or habituation is shown by the improvements gained by repeating the posturographic tests (Figure 3). At the start of each day, the response to the perturbations was controlled more efficiently than then at the start of the previous day. Based on previous experience, normal subjects were able to further refine the strategy and reduce the energy expended on correctional movements to maintain balance and to withstand the perturbations.

Discussion

Adaptation to a novel postural challenge causes the generation of a modified motion strategy, reflected by both quantitative and qualitative alterations of the body sway responses. However, there is large interindividual variation in the adaptation pattern. Some subjects rapidly select a more resilient posture and suppress the effects of stimulation, whereas others adjusted their responses over a longer period [25]. This suggests that there exists a large variety of dynamic strategies, rather than a single particular configuration that assures stability [10], [26]. The properties of the adaptive adjustments imply that at least three partly independent adaptive processes are involved in the formation of new motor programs that are able to consider and suppress postural disturbances such as vibratory proprioceptive stimulation: 1) suppression of the individual vibratory perturbation, 2) adoption of a posture that is better able to withstand the disturbances, 3) use of the experience from previous exposures to withstand vibratory stimulation when the trial is repeated. These adaptive processes can be manipulated separately and act at different time scales [13], [14], [25], [27].

The first adaptive process can be seen in the progressive reduction of body sway induced by the stimulation during tests, which might be caused by reweighting the available sensory inputs. The movements induced by stimulation of a single sensory input will be detected by other sensory receptors, and the sensory mismatch could be reduced by reweighting the sensory information to more reliable sensory inputs [9], [23]. The suppression of mismatching disturbances from sensory lesions by reweighting the sensory information is most likely an important part of the adaptation and rehabilitation process. The movement responses to stimulation are primarily changed during the initial 100-120 seconds, which contained 25-35 perturbations in our particular sequence. This number of perturbations appears to be sufficient to instigate a new or improved control strategy [28], [29] that reduces the effects of vibratory stimulation. Thus, within a relatively short timeframe, healthy humans are able to adapt and adjust their

Fig. 2. The graphs show measured anteroposterior and lateral torque during quiet stance and during pseudorandomized vibratory stimulation applied to the gastrocnemius muscles. The data were sampled from a normal test subject standing with eyes closed. The mean anteroposterior position during the trial is set to zero, and the lateral position is arbitrarily offset for the quiet stance period and the consecutive 50-s stimulation periods. Note the sway difference between quiet stance compared to the stimulation periods as well as the changes in sway amplitude and body position over time.

postural control and multijoint movement patterns in order to reduce the effect of repeated postural disturbances or effects of muscle fatigue [30]-[32].

The adaptive adjustments to the individual perturbations are combined with a second adaptive process: "strategic" adjustments of body posture or body kinematics such as leaning forward [2], [3], [6]. Perturbations evoked by vibratory stimulations induce simultaneous body movements in all body segments, corresponding to an approximate single-link pendulum pattern [20], [33]. Since ankle joint stiffness depends on the moment carried by the joints [34], there is a possibility that by leaning more or less forward a proper level of ankle stiffness can be chosen by adjusting the postural alignment. In terms of motion control, a more rigid body posture might have several advantages. A co-contraction of the antagonistic muscle groups increases the stiffness of a joint and increases the damping of the induced motions [35]. The overall effect is increased mechanical stability, though at a greater metabolic cost [36]. Buchanan et al. observed that the muscle activity patterns and multijoint movement patterns were altered by the frequency of the support surface translation without loss of stability [37]. This finding suggests that the postural control system, without suffering loss of stability, is able to gradually alter the kinematical properties by recruiting or suppressing the biomechanical degrees of freedom. Moreover, reducing the degrees of freedom of the object to control (i.e., the stability of the human body) to only one segment with single-link pendulum characteristics may considerably simplify the control task at hand. Novice subjects learning a new skill may utilize this strategy of reducing the number of degrees of freedom [38].

A third more long-term adaptive process or habituation is shown by the improvements gained by repetition of posturographic tests. At the start of each day, the response to the perturbations was controlled more efficiently than at the start of

the previous day. Based on previous experience, subjects were able to further refine the strategy and reduce the energy expended on correctional movements to maintain balance and to withstand the perturbations [24], [39]. A comparison between the results from the initial five days of consecutive testing and the tests performed after 90 days shows that normal subjects retained their capability to respond appropriately to the stimulus [24]. Thus, previous experience of the test situation and the perceived level of postural threat during the test situation have a profound long-term influence on postural control [24], [30], [40]. This suggests that the vibratory perturbation elicits the development of a long-term memory or a strategy for this specific kind of stimulation [41]. This process of adaptation could be defined as "consolidation, as the postural strategy during inactivity has been refined and the motor responses further improved [41].

Conclusions

The presented findings suggest that patients with balance disorders would benefit from rehabilitation programs that include a mixture of exercises aimed at training specific motor tasks or motor programs. The exercises should be repeated with intervals and be sufficiently long and challenging if to initiate by active learning a process of adaptation and habituation. Moreover, in the clinical follow-up, the adaptation to the test situations should be considered if balance tests such as posturography are repeated regularly on patients suffering from balance disorders. Measured improvement may not all be due to recovery but merely an effect of adaptation to the examination environment itself.

Per-Anders Fransson received the master of science degree in electrical engineering in 1991 from Lund University, Lund, Scandinavia. He is member of Swedish Vestibular Society. In his scientific work, he has been involved in research in mathematical modeling of adaptive systems, system identification, signal processing analysis, and biomechanical research. Since 1991, he has participated in research at the Vestibular Laboratory within the Department of Otorhinolaryngology, Lund University Hospital, where he also has been an advisor to students presenting master of science and projects.

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Fig. 3. Mean normalized variance ($\text{Nm}/(\text{Kg}\cdot\text{m})^2$) for a group tested with eyes closed consecutively for five days with posturography. The graph shows the body sway variance during the five days and during four consecutive 50-s periods during the vibratory stimulation from the trial each day (denoted 1-4, from the time periods 30-80, 80-130, 130-180, and 180-230 seconds, respectively). The body sway during quiet stance for 0-30s is not shown in the figure. Note the sway reduction during each day's test and between tests on consecutive days.

ish Society of Medicine for distinguished contribution to the study of human balance through application and development of system analysis and robotics. In 1993 he published the book *System Modeling and Identification* [Prentice Hall, Englewood Cliffs, NJ (Information and System Sciences Series Ed. T. Kailath)]. Currently he is coordinating robotics research with participants from several departments of Lund University.

Fredrik Tjernström graduated as M.D. in 2001. He is now a second-year resident in otorhinolaryngology as well as a research student in otoneurology, where he specializes in adaptive process in postural control.

Måns Magnusson received his M.D. in 1981 and became an approved specialist in otorhinolaryngology in 1987. In 1987 he was accepted as a faculty member in the ENT clinic at the University Hospital of Lund. In 1988 he was made associate professor. In 1992 he became consultant and in 1996 senior consultant in ENT. In 1996 he

was assigned director of undergraduate studies in otolaryngology. In 1997 he was promoted to a side chair professorship of otolaryngology and in 1999 to full professor. He has been the primary investigator and in charge of research in the vestibular lab since 1985 and in charge of clinical work since 1988. He has published more than 90 papers in reviewed medical and science journals, mostly in the field of otoneurology. He is a member of the Barany Society, International Society of Posture and Gait Research, European Academy of Neurotology and Otology (advisory board member), and the Swedish Medical Association.

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