Comparison of Non-Volitional Postural Responses Induced by Two Types of Torso Based Vibrotactile Stimulations

Beom-Chan Lee*
Department of Mechanical Engineering, University of Michigan

Bernard J. Martin†
Department of Industrial and Operations Engineering, University of Michigan

Kathleen H. Sienko‡
Department of Mechanical Engineering, University of Michigan

ABSTRACT

The purpose of this study was to characterize the non-volitional postural responses to torso-based vibrotactile stimulation as a function of stimulation location for two types of vibrating actuators (tactors). Eleven young healthy adults were asked to maintain an upright erect posture with their eyes closed. Two types of tactors, Tactaid (electromagnetic inertial transducer) and C-2 (voice-coil-type linear transducer), were placed over the left and right external oblique, internal oblique, and erector spinae muscles in two different trial series. Regardless of the tactor type, vibration applied over the internal oblique and erector spinae muscles induced a postural shift in the direction of the stimulation. For these four locations, the root-mean-square (RMS) of the sway was significantly greater during vibration than immediately before or after stimulation. Vibration-induced postural shifts and increases in RMS sway were greater for the C-2 than Tactaid tactors. Simultaneous activation of all tactors or those over the external oblique muscles did not produce significant directional postural shifts or increases in sway, regardless of the tactor type. The directional shifts of posture suggest that these non-volitional responses should be considered to improve the use of torso-based vibrotactile sensory augmentation display designed for clinical balance applications.

KEYWORDS: Posture control, vibrotactile stimulation, directional response, tactor type.

INDEX TERMS: H.5.1 [Information Interfaces and Representation (HCI)]: User Interfaces—Haptic I/O; H.1.2 [User/Machine Systems]: User/Machine Systems—Human factors;

1 INTRODUCTION

Vibrotactile displays are human-computer interfaces that use tactation to convey spatial or situational information such as navigational instructions for individuals with visual impairments [1], attitude or threat warning information to aircraft pilots [2], and orientation and proximity information to foot soldiers [3].

In recent years, vibrotactile displays that provide information about body motion with respect to the gravito-inertial vector have been used in balance-related applications to induce corrective motor responses. These responses were associated with decreased postural sway in individuals with vestibular deficits [4-5], older adults [6], and young healthy adults [7] during quiet and perturbed stances. To date, the most common vibrotactile displays for balance-related applications include an array of electromechanical actuators located horizontally along a belt worn around the torso [4-7].

Repulsive cuing strategies, for which individuals are instructed to move in the direction opposite to the vibration, have been used traditionally for these applications. Wall et al. [8] assumed that vibration may provoke an aversion response, as when encountering an obstacle. Subsequent studies have employed a similar scheme. However, the postural adjustment is simply considered as a volitional response to a warning signal, which may not be congruent with possible kinesthetic information from the stimulated tactile receptors. Previous studies have shown that cutaneous receptors located in the skin around the finger, elbow, ankle, and knee joints provide exteroceptive and proprioceptive information [9-12]. Similar to muscle spindles, these receptors encode movement kinematics and show directional sensitivity [9-12]. However, the contribution of cutaneous receptors to spatial representation of the torso and postural control had not yet been investigated. This motivated our previous investigation, in which in the absence of instructions, young healthy adults were found to move in the direction of the vibrotactile stimulation when C-2 tactors placed over the internal oblique and erector spinae muscles were activated [13].

The purpose of the present study was to assess whether the type of tactor used has an effect on the direction and/or magnitude of the postural response. The results from this study will inform the design of a tactor display for balance-related applications.

2 METHOD

2.1 Subjects

Eleven young healthy adults (7 males, 4 females, mean age 22.9 ± 4.8 yrs) naïve to the purpose of the experiments participated in this study. Exclusion criteria included any central neurologic dysfunction, functionally significant musculoskeletal dysfunction, or a body mass index greater than 30 kg/m^2. The study, which conformed to the Helsinki Declaration, was approved by the University of Michigan Institutional Review Board.

2.2 Instrumentation

The experimental apparatus was composed of a commercial six degree-of-freedom inertial measurement unit (IMU; Xsens Technologies, NL), two sets of six tactors, a laptop computer, and a vibration control circuit. The IMU signals indicating angular displacements, velocities, and accelerations in the anterior-posterior (A/P) and medio-lateral (M/L) directions were sampled at a rate of 100Hz. The IMU was attached to the back of the torso at approximately the L3 vertebra level. Tactaid and C-2 tactors, two of the most common vibrotactile actuators, were used to generate tactile stimulations. The Tactaid VBW32 tactor (Audiological Engineering Corp., USA) is an inertial transducer, which consists of a rigid case, inside which a mass is suspended on a spring [14]. Both the mass and the case vibrate when an alternating electromagnetic force is generated. The C-2 tactor (Engineering Acoustics Inc., USA) is a voice-coil-type linear actuator that incorporates a moving contactor lightly preloaded

*e-mail: channy@umich.edu
†e-mail: martinbj @umich.edu
‡e-mail: sienko@umich.edu

IEEE Haptics Symposium 2012
4-7 March, Vancouver, BC, Canada
978-1-4673-0809-0/12/$31.00 ©2012 IEEE

against the skin [14]. The contactor oscillates perpendicularly to the skin, while the surrounding skin area is shielded with a passive housing. Both types of tactors generate a vibration normal to the surface of the skin. Six tactors (i.e., either six Tactaid or C-2 tactors) were placed on the skin over the left and right internal oblique, external oblique, and erector spinae muscles approximately at the level of the iliac crest, which corresponds to the L4/L5 vertebrae level. The IMU and the tactors were attached with Velcro to an elastic belt worn around the torso. Tactors were driven by a 250 Hz sinusoidal signal in order to maintain the stimulation within the one-to-one frequency response of fast-adapting cutaneous receptors [15] and avoid the response of muscle spindles [16].

2.3 Procedure

Subjects stood on a firm surface, eyes closed with their arms held at their sides and their feet hip-width apart at a 15° lateral rotation angle. Foam ear plugs and ear muffs were worn to eliminate environmental noise.

Each trial was composed of consecutive measurement periods that included an initial period of 5 s without vibrotactile stimulation followed by 5 s vibration period. A 5 s post vibration period was recorded for a subset (n=5) of the subjects. Each subject was subjected to two distinct series of trials while wearing either the Tactaid or C-2 tactors. The initial tactor type was randomly assigned to each subject. During the experimental protocol tactors were either individually (referred to as "single location" stimulation) or simultaneously (referred to as "all locations") activated. Two trials for each stimulation condition were performed in a random order, which corresponded to a total of 14 trials for each tactor type per subject (i.e., six "single locations" and one "all locations" trials across a series). No information was provided to subjects regarding tactor types, tactor locations, or the duration of vibration signals. Note that each subject was asked to maintain an upright erect posture behaving as inverted pendulums during the experimental trial. At the end of the protocol subjects were asked to indicate which set of tactors (1^{st} or 2^{nd}) generated the strongest vibration.

2.4 Data analysis

MATLAB (The Math Works, Natick, MA) was used to process the IMU-captured postural sway signals. For data analysis, the "pre-vibration" and "post-vibration" periods were defined as the 5 s preceding and following the vibrotactile stimulation (per-vibration period), respectively.

In order to determine the magnitude and direction of postural responses between the consecutive periods of interest (pre-/per- and per-/post-vibration periods), 95% confidence interval ellipses were fit to the 2D postural trajectories for each period. The center of each ellipse was used to calculate the 2D postural shift vector for the pre-, per-, and post-vibration periods. Detailed information regarding the data analysis methods are presented in [13]. A/P and M/L root-mean-square (RMS) values of the angular displacements of the body (sway) as a function of pre-, per-, and post-vibration periods were computed. The magnitudes and directions of the postural shift values as well as the A/P and M/L RMS sway values were computed for each subject and each period as a function the stimulation location and tactor type.

A three-way repeated measure analysis of variance (ANOVA) was conducted to determine the main effects of tactor type (C-2, Tactaid), location (six "single locations" and the "all locations" conditions), and period (pre-, per- and post-vibration) for each dependent variable (e.g., magnitude, direction, A/P RMS, and M/L RMS of postural sway). Hypotheses for the main effects of condition and measurement period as well as their interactions were tested using a F-test. To determine which factors influenced the main and interaction effects, post-hoc tests (Tukey Honestly Significant Differences - HSD - for multiple comparisons) were also conducted. The level of significance was set at $p < 0.05$. To assure the assumptions of normality and constant variance of residual variance, both A/P and M/L RMS sway values were transformed to a logarithmic scale.

3 Results

3.1 Magnitude and Direction

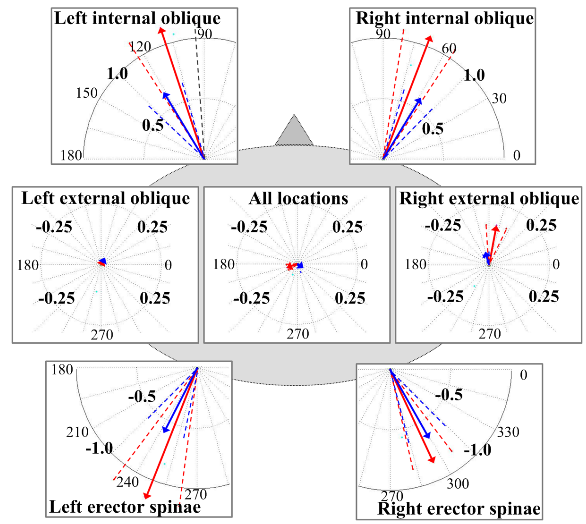

Figure 1. Average postural shift vectors during per-vibration periods as a function of tactor location. Red and blue vectors correspond to the C-2 and Tactaid stimulations, respectively. Dash lines indicate the standard error of the corresponding vector direction.

Figure 1 shows the postural shift vectors during the per-vibration period as a function of the stimulation condition and tactor type. Note that the pre-vibration postural shift vectors were subtracted from the per-vibration vectors for representation purposes.

The ANOVA applied to the postural shift vectors (i.e., postural shift magnitude and direction) indicated that the main effects of tactor type, location, and period as well as the tactor type x location and the location x period interactions were significant, as shown in Table 1. Post-hoc analysis showed that the magnitude of the postural shift vectors during the per-vibration period was significantly greater than that during the pre- and post-vibration periods for both types of tactors (Tactaid: $p < 0.01$ and C-2: $p < 0.02$, Tukey HSD) when vibration was applied over the internal oblique and erector spinae locations. For each tactor type, however, the relative magnitudes of the postural shift vectors during vibration were similar between the aforementioned four locations. When vibration was applied over the right and left internal oblique muscles, subjects exhibited a postural shift in the forward right and forward left directions, respectively. When vibration was applied over the erector spinae, the body posture shifted in the backward left and backward right directions, respectively. Upon cessation of vibration, the body posture shifted in the direction opposite to the postural shift observed during vibration. Furthermore, the magnitudes and directions of the postural shift vectors did not significantly change when vibration was applied to all locations simultaneously or when it was applied over the external obliques, regardless of the tactor type.

Figure 2(a) shows the average magnitude of the postural shift vectors during the per-vibration period as a function of tactor location for each tactor type. The magnitudes of the postural shift vectors were significantly greater with the C-2 than Tactaid tactors when vibration was applied over the internal oblique and erector spinae locations. The average magnitude of the vibration-induced postural shift was approximately 0.7° for Tactaid and 1.2° for C-2 tactors for the internal oblique and erector spinae locations. Assuming that postural corrections were primarily driven by ankle rotation (i.e., inverted pendulum behavior), these shifts correspond to a head displacement of 2.14 cm (Tactaid) and 3.68 cm (C-2) for a 50th percentile male and 1.99 cm (Tactaid) and 3.41 cm (C-2) for a 50th percentile female [17].

Dependent variable	Effects	DF	F Value	Pr>F
Postural shift magnitude	T	1, 420	15.71	< 0.0001*
	L	6, 420	25.14	< 0.0001*
	P	2, 420	62.36	< 0.0001*
	T x L	6, 420	4.21	< 0.0001*
	T x P	2, 420	0.61	0.545
	L x P	12, 420	4.20	< 0.0001*
	T x L x P	12, 420	0.98	0.470
Postural shift direction	T	1, 420	13.38	< 0.0001*
	L	6, 420	7.86	< 0.0001*
	P	2, 420	57.54	< 0.0001*
	T x L	6, 420	3.24	0.010*
	T x P	2, 420	2.11	0.123
	L x P	12, 420	3.86	< 0.0001*
	T x L x P	12, 420	0.91	0.540
A/P RMS	T	1, 420	13.49	< 0.0001*
	L	6, 420	51.32	< 0.0001*
	P	2, 420	70.37	< 0.0001*
	T x L	6, 420	2.59	0.018*
	T x P	2, 420	0.71	0.492
	L x P	12, 420	1.91	0.032*
	T x L x P	12, 420	0.50	0.913
M/L RMS	T	1, 420	10.87	0.001*
	L	6, 420	60.63	< 0.0001*
	P	2, 420	55.806	< 0.0001*
	T x L	6, 420	2.41	0.026*
	T x P	2, 420	0.74	0.480
	L x P	12, 420	4.99	< 0.0001*
	T x L x P	12, 420	0.298	0.990

Table 1. Statistical results of each dependent variable for the main effects (i.e., tactor type (T), location (L), and period (P)) and their interactions. * Statistical significance.

3.2 RMS

The ANOVA applied to RMS sway indicated that the main effects of the tactor type, location, and period as well as the tactor type x location and the location x period interactions were significant in both the A/P and M/L directions, as shown in Table 1. Post-hoc analysis showed that the A/P and M/L RMS sway were significantly greater (Tactaid: $p < 0.02$ and C-2: $p < 0.014$, Tukey HSD) during the per- and post-vibration periods than during the pre-vibration period when vibration was applied over the internal oblique and erector spinae locations. For each tactor type, however, the A/P and M/L RMS sway during the per- and post-vibration periods were statistically equivalent between the aforementioned four locations. Regardless of the tactor type, this analysis also showed that the A/P and M/L RMS sway values during the pre-vibration period were not significantly different across the six single locations. Further, the A/P and M/L RMS sway values during the per-vibration period were similar for the left and right internal oblique and erector spinae locations for each tactor type. However, changes in the A/P and M/L RMS sway were negligible when vibration was applied over the external obliques or at all locations, regardless of the tactor type.

Comparisons of the average RMS sway during vibration for each tactor type as a function of tactor location are illustrated in Figure 2(b). The A/P and M/L RMS sway magnitudes were significantly greater with the C-2 than the Tactaid tactors when vibration was applied over the internal oblique and erector spinae locations.

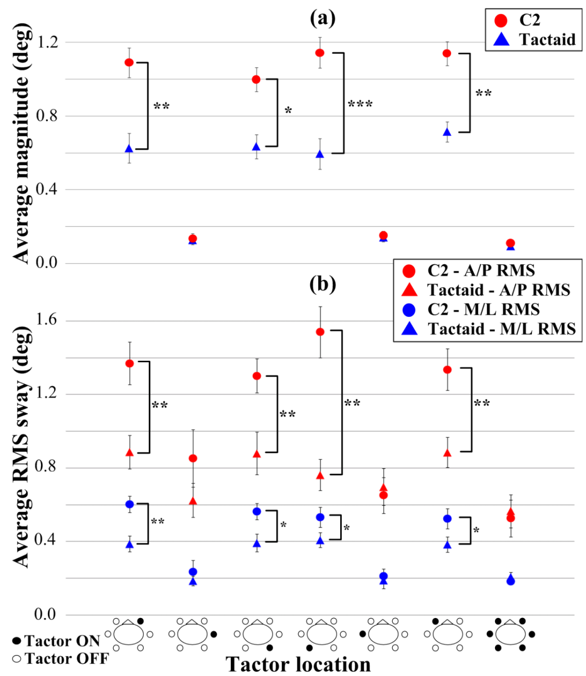

Figure 2. (a) Average magnitude of the postural shift vector for the C-2 (●) and Tactaid (▲) tactors during the per-vibration period as a function of tactor location. (b) Average A/P and M/L RMS sway for the C-2 (●) and Tactaid (▲) tactors during the per-vibration period as a function of tactor location. Red and blue symbols represent the A/P and M/L RMS sway, respectively. Error bars indicate standard error of the mean. *$p < 0.05$, **$p < 0.01$, ***$p < 0.0001$. Bird's-eyeview drawings illustrate vibration locations.

4 Discussion

The results suggest that cutaneous information from the skin over torso muscles contribute to an internal representation of the upper body and its orientation. This interpretation is in agreements with investigations by Aimonetti et al. [9], Collins et al. [10], and Lackner and Levine [12] who showed that cutaneous receptors located in the skin around the finger, elbow, knee, and ankle joints provide exteroceptive and proprioceptive information. Edin [18] and Kavounoudias et al. [19] have shown that, similar to muscle spindles, cutaneous receptors encode movement kinematics and show directional sensitivity. Furthermore, our results show that vibration-induced compensatory postural shifts oriented in the direction of vibration application are similar in direction to those produced by muscle vibration [20]. Indeed, the directional shift was congruent with a postural response to a muscle lengthening, which would stretch the skin, as is the case when vibrations stimulate muscle spindles [20].

Both vibration-induced postural shifts and increases in RMS sway were significantly greater with the C-2 than the Tactaid tactors when vibration was applied over the internal oblique and erector spinae muscles. In order to compare the relative vibration amplitudes of the two types of tactors, we constructed a measurement apparatus comprising a Laser Doppler Vibrometer, simulated skin substrate, and adhesive. The amplitude of the C-2 tactor vibration (≈ 200 µm, peak to peak displacement) was approximately five times that of the Tactaid tactor (≈ 50 µm, peak to peak displacement). Vedel and Roll [21] and Ribot-Ciscar et al. [15] have shown that mechanoreceptors are very sensitive to mechanical vibration with stimulations in the range of a 200-500 μm peak to peak displacement. Subjects in this study reported that the perceived vibration intensity was greater for the C-2 than the Tactaid tactors. This difference in perception is in agreement with the difference in postural responses and well correlated with the stimulation amplitude. Furthermore, Kavounoudias et al. [22] and Wierzbicka et al. [23] have shown that muscle response increased with stimulation magnitude. In addition, Martin et al. [24] showed that the strength of vibration-induced proprioceptive activity increases with vibration magnitude. Therefore, it is assumed that, due to the greater strength of the C-2 tactor, a larger number of tactile receptors are recruited by mechanical stimulation, which in turn increases the associated compensatory response. As indicated earlier, it is unlikely that the largest vibration of the C-2 tactors would significantly activate the primary endings of the muscles located under the skin.

Vibration applied to the skin over the external oblique muscles did not induce a significant shift, regardless of the tactor type. Indeed, postural stability is usually greater in the M/L than A/P direction during normal stance [20] and, in the present study, hip-width separation of the feet also contributed to a high lateral stability. Hence, a small vibration-induced change in sensory information is less likely to alter postural stability in the direction corresponding to the action of these muscles.

To conclude, vibrations applied to the skin over the internal oblique and erector spinae muscles induced postural shifts in the direction of the vibration location, regardless of tactor type. The compensatory response corresponds to an attraction in the direction of the stimulated area. Vibration-induced postural shifts for internal oblique and erector spinae locations were greater with the C-2 (1.2°) than Tactaid (0.7°) tactors, indicating that the magnitude of postural responses increased with vibration strength. Our findings strongly support the contribution of cutaneous information from receptors located over the torso's primary mover muscles to posture regulation and spatial representation of the torso, which was attributed primarily to muscle proprioception [25]. Therefore, tactor type and application locations should be carefully considered and the instructions concerning reactive/corrective movements should be compatible with the non-volitional response to the vibrotactile stimulation in order to facilitate postural adjustments.

Acknowledgments

This work was supported by a NSF CAREER grant (RAPD-0846471) to K Sienko. The Center for Statistical Consultation and Research at University of Michigan provided support for the statistical analysis. We thank K Grosh and his student K Knisely for use of and assistance with the Laser Doppler Vibrometer.

References

[1] J. Van Erp, "Presenting directions with a vibrotactile torso display," *Ergonomics,* vol. 48, no. 3, pp. 302-13, Feb 22 2005.

[2] H. A. H. C. Van Veen and J. B. F. Van Erp, "Tactile Information Presentation in the Cockpit," in *Haptic Human-Computer Interaction*, Tokyo, JAPAN, 2001, pp. 174-181.

[3] J. C. Brill, R. D. Gilson, M. Mouloua, P. A. Hancock, and P. I. Terrence, "Increasing situation awareness of dismounted soldiers via directional cueing," in *Human Performance, Situation Awareness and Automation: Current Research and Trends*, D.A. Vincenzi., M. Mouloua, and P.A. Hancock (Eds.), Mahwah, NJ: Erlbaum, 2004.

[4] K. H. Sienko, V. V. Vichare, M. D. Balkwill, and C. Wall, "Assessment of vibrotactile feedback on postural stability during pseudorandom multidirectional platform motion," *IEEE Trans Biomed Eng,* vol. 57, no. 4, pp. 944-952, 2010.

[5] C. Wall and E. Kentala, "Control of sway using vibrotactile feedback of body tilt in patients with moderate and severe postural control deficits," *J Vestib Res,* vol. 15, no. 5-6, pp. 313-325, April. 2005.

[6] S. Haggerty, L. T. Jiang, A. Galecki, and K. H. Sienko, "Effects of vibrotactile feedback on response time and postural stability in older adults," *Gait & Posture* (in press).

[7] B. C. Lee, J. Kim, S. Chen, and K. H. Sienko, "Cell phone based balance trainer," *J Neuroengineering Rehabil* (in press).

[8] C. Wall, M. S. Weinberg, P. B. Schmidt, and D. E. Krebs, "Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt," *IEEE Trans Biomed Eng,* vol. 48, no. 10, pp. 1153-1161, 2001.

[9] J. M. Aimonetti, V. Hospod, J. P. Roll, and E. Ribot-Ciscar, "Cutaneous afferents provide a neuronal population vector that encodes the orientation of human ankle movements.," *J Physiol,* vol. 580, no. 2, pp. 649-658, Apr. 2007.

[10] D. F. Collins, K. M. Refshauge, G. Todd, and S. C. Gandevia, "Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee," *J Neurophysiol,* vol. 94, no. 3, pp. 1699-1706, Sep. 2005.

[11] Y. P. Ivanenko, V. L. Talis, and O. V. Kazennikov, "Support stability influences postural responses to muscle vibration in humans," *Eur J Neurosci,* vol. 11, no. 2, pp. 647-54, Feb 1999.

[12] J. R. Lackner and M. S. Levine, "Changes in apparent body orientation and sensory localization induced by vibration of postural muscles: vibratory myesthetic illusions," *Aviat Space Environ Med,* vol. 50, no. 4, pp. 346-54, Apr 1979.

[13] B. C. Lee, B. J. Martin, and K. H. Sienko, "Directional postural responses induced by vibrotactile stimulations applied to the torso," submitted.

[14] R. W. Cholewiak and M. Wollowitz, "The design of vibrotactile transducers," in *Tactile Aids for the Hearing Impaired*, I. Summers (Ed.), pp. 57-82, London: Whurr Publishers Ltd, 1992.

[15] E. Ribot-Ciscar, J. P. Vedel, and J. P. Roll, "Vibration sensitivity of slowly and rapidly adapting cutaneous mechanoreceptors in the human foot and leg," *Neurosci Lett,* vol. 104, no. 1-2, pp. 130-135, 1989.

[16] D. Burke, K. E. Hagbarth, L. Löfstedt, and B. G. Wallin, "The response of human muscle spindle endings to vibration of non-contracting muscles," *J Physiol,* vol. 261, no. 3, pp. 695-711, 1976.

[17] D. B. Chaffin, G. B. J. Andersson, and B. J. Martin, *Occupational Biomechanics*. New York: Wiley-Interscience, 2006.

[18] B. B. Edin, "Quantitative analysis of static strain sensitivity in human mechanoreceptors from hairy skin," *J Neurophysiol,* vol. 67, no. 5, pp. 1105-1113, May. 1992.

[19] A. Kavounoudias, R. Roll, and J. P. Roll, "Specific whole-body shifts induced by frequency-modulated vibrations of human plantar soles," *Neurosci Lett,* vol. 266, no. 3, pp. 181-184, May. 1999.

[20] B. J. Martin, G. M. Gauthier, J. P. Roll, M. Hugon, and F. Harlay, "Effects of whole-body vibrations on standing posture in man," *Aviat Space Environ Med,* vol. 51, no. 1, pp. 778-787, Aug. 1980.

[21] J. P. Vedel and J. P. Roll, "Response to pressure and vibration of slowly adapting cutaneous mechanoreceptors in the human foot," *Neurosci Lett,* vol. 34, no. 3, pp. 289-294, 1982.

[22] A. Kavounoudias, R. Roll, and J. P. Roll, "Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation," *Journal of Physiology,* vol. 532, no. Pt 3, pp. 869-878, May. 2001.

[23] M. M. Wierzbicka, J. C. Gilhodes, and J. P. Roll, "Vibration-induced postural posteffects," *Journal of Neurophysiology,* vol. 79, no. 1, pp. 143-150, Jan. 1998.

[24] B. J. Martin, J. P. Roll, and G. M. Gauthier, "Inhibitory effects of combined agonist and antagonist muscle vibration on H-reflex in man," *Aviat Space Environ Med,* vol. 57, no. 7, pp. 681-687, Jul. 1986.

[25] J. P. Roll, J. P. Vedel, and E. Ribot, "Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study," *Exp Brain Res,* vol. 76, no. 1, pp. 123-222, 1989.