Acta of Bioengineering and Biomechanics
Vol. 24, No. 3, 2022

Original paper
DOI: 10.37190/ABB-02116-2022-01

The effect of a light finger touch on the signal complexity during quiet standing

ANNA BRACHMAN[1], ANNA SAWICKA[1], BARTŁOMIEJ BEDNARZ[1], ANNA AKBAŞ[2], KAJETAN J. SŁOMKA[2]

[1] Institute of Sport Sciences, Department of Biomechanics, The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland.
[2] Institute of Sport Sciences, Department of Human Motor Behavior, The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland.

The purpose of the study was to investigate the influence of additional tactile information (light fingertip touch) on the postural sway and regularity of center-of-pressure (COP) fluctuations. Thirty-two young, healthy participants performed a quiet standing task (30 s) on a force platform with and without light fingertip touch. COP time-series were analyzed using standard postural sway measures (range, root mean square error, velocity), COP regularity was measured with Sample entropy. Participants demonstrated significantly smaller postural sway with a light touch, but only in the anteroposterior direction. The amount of sway with additional tactile information in the sagittal plane reached the level of sway in the frontal plane without this information. Similarly, COP fluctuations were more irregular during light touch condition only in the anteroposterior direction, as evidenced by significantly higher Sample entropy. Furthermore, COP regularity decreased in the sagittal plane and reached level in the frontal plane without light touch. These results suggest that postural sway is mostly controlled in the sagittal plane and that in the mediolateral direction the control is mostly automated. In conclusion, our results support the notion that the light touch provides additional information which enhances postural stabilization. Our results expand the relation between COP regularity and the attention invested in posture in the touch domain and prove that light touch, as an attentional demanding task, leads to increased COP irregularity. Nonlinear measures of signal regularity (i.e., SampEn) provide surplus insight into human postural control and can be used as an additional useful tool to traditional balance measures.

Key words: *postural control, light touch, center-of-pressure regularity, postural balance*

1. Introduction

Maintaining an upright standing posture is a complex task that involves various sensory and motor components [5]. Naturally, human body is in constant motion during standing and the central nervous system uses different sources of information to attenuate this postural sway [19].

The key sensory inputs come from visual, vestibular and somatosensory stimuli [6], [19]. The somatosensory system particularly uses proprioceptive, pressure and touch sensors, which provide feedback about the position of body segments in relation to each other and to the environment, they also inform about contact with external material objects [32].

Numerous studies exploring dual-task paradigm have confirmed that balance control requires a certain amount of attention [33]. Even tasks considered as "automated" require some attentional resources [31]. The stimulus-response reaction times, which evaluate attentional involvement, have been reported in previous papers to increase with postural task difficulty [13], [14], [29], aging [13] or inferior postural skills [29], [31]. It was also proven that the amount of attention required for controlling posture depends on the availability of the sensory information [28], [30], [33].

* Corresponding author: Anna Brachman, PhD, Department of Biomechanics, The Jerzy Kukuczka Academy of Physical Education in Katowice, ul. Mikołowska 72A, Katowice, Poland. Phone: +48 32 207 51 41, fax: +48 32 207 52 00, e-mail: a.brachman@awf.katowice.pl
Received: July 29th, 2022
Accepted for publication: October 13th, 2022

In the literature, it is well known that the light touch of the index fingertip to a rigid surface reduces the magnitude of postural sway [1], [9], [11], [17], it is also said that the effect of direction stabilization is related to the touch position [11], [16], [21]. Additionally, numerous papers reported significant influence of the light touch on the sagittal plane during side-by-side quiet standing (while standing comfortably with feet positioned naturally or approximately shoulder-width apart), whereas the frontal plane was not analyzed, reported or no significant influence on postural sway was observed [5], [9], [16], [17], [21].

According to the sensory hypothesis proposed by Jeka and Lackner [11], additional information given from tactile and other sensory receptors provide feedback concerning position of the hand and arm in the space. It is acting as an additional spatial point of reference for postural stabilization during quiet standing [1], [5], [30]. It has been also shown that use of a light touch as a source of sensory information leads to an increase in reaction time for an auditory stimuli during quiet standing, which suggests that the process is attentionally demanding [30].

In the last decade, the use of nonlinear dynamics in conjunction with traditional balance measures helped to understand the neuromuscular status of the person's postural control and offers additional insights into the balance control strategies [10], [18], [20]. The hypothesis proposed in the literature says that the dynamical structure of the center of pressure (COP) (expressed by Sample entropy level) is positively related to the amount of attention involved in the control of the upright posture [2], [23], [24], [27]. Previous reports state that COP time-series regularity during standing were increased in stroke patients, compared to healthy participants, and it was decreasing instantaneously during the execution of a cognitive dual task as well as in the course of patients' rehabilitation [23]. A less complex signal was also reported for other somatosensory deficiencies [3]. For healthy participants, divert attention from posture by doing a cognitive dual task [4], [8], [27] or drawing attention to the external focus increased the level of irregularity [2], [20]. In contrast, the increased difficulty of the postural task through the adoption of a more demanding posture or the suppression of vision (internal focus) has led to an increase in the regularity of the COP [8], [24], [27]. Moreover, Donker et al. [8] reported that the increase in cognitive involvement in postural control induced by visual deprivation resulted in an increase in signal regularity only in the sagittal plane. Also Roerding et al. [23] showed that, in healthy older adults, regularity of the COP signal was higher in the anteroposterior direction. Hence, the authors concluded that posture in healthy subjects is mainly controlled in the sagittal plane [8].

In the present study, we sought to extend these findings to the touch domain and evaluate the influence of the additional tactile information on the level of the COP irregularity. As the results of the influence of the light touch on the postural control are often reported only in one direction, we have extended our analysis to both directions. Given the above, we hypothesized that additional tactile information leads to a decrease in the amount of sway in the anteroposterior direction without influencing the mediolateral direction. We also hypothesized that the additional somatosensory information provided by cutaneous receptors (light touch) leads to withdrawal of attention from the body posture, thereby leading to an increase in COP irregularity. Furthermore, we hypothesized that regularity during quiet standing is greater in the anteroposterior direction.

2. Materials and methods

2.1. Participants

Thirty-two healthy students (17 women, 15 men; age: 22 ± 2 years (mean ± SD), body weight: 71 ± 14 kg, height: 175 ± 9 cm) from Academy of Physical Education in Katowice participated in this study. They were naïve about the subject of the study. They gave their written and informed consent to the experimental process required by the Declaration of Helsinki and the local ethics committee. None of them had any current or previous medical history of muscular, skeletal or neural disorders that could influence the results. All participants were right-handed with normal or corrected-to-normal vision. The limb dominance was declared by the participants and was consistent with the hand they used for writing.

2.2. Apparatus and data analysis

All measurements were done with the use of a force platform (AMTI AccuGait, MA, USA). The anterior–posterior (AP) and mediolateral (ML) center of pressure (COP) fluctuations were recorded at 100 Hz sampling frequency. The raw COP data were filtered with a 4th, low-pass Butterworth filter, a cut-off frequency of 7 Hz using the MATLAB r2017b software

(Mathworks Inc., Natick, MA, USA), and four amplitude variables were examined: area [cm^2], range [cm], root mean square error [cm], mean velocity [cm/s]. For the regularity analysis, the Sample entropy was used and, according to the recommendations, the COP signal was not filtered [18], [20], [26]. The lower level of Sample entropy express higher regularity of the time-series. To optimize the choice of template vector [m] and tolerance level [r] the minimization of the maximum entropy relative error method was adopted [15]. For the present study, $m = 2$ and $r = 0.05 \times$ SD were used.

2.3. Procedures

Participants stood barefoot on the force platform with their big toes touching the line marked on the platform, feet were parallel, positioned at shoulder width. Participants were asked to stand still as possible in two conditions, with additional tactile information (light touch – LT) and without light touch (NoLT). In each condition, participants were asked to fixate their gaze on a point located 3 m away at their eyes level. In the light touch condition (Fig. 1), participants were instructed to maintain their elbow flexed approximately at 90°, wrist in the neutral position and the index fingertip of a dominant hand in contact with the rigid surface attached to the tripod placed on the narrow support area, in such way that it would overturn if too much force were applied. Similar solution was adopted previously [5], [22]. The height of the tripod was adjusted to keep the participant's elbow flexed at approximately 90 degrees while touching the plate with index fingertip [5]. The non-dominant arm hung passively along their side. To create most natural conditions for controlling upright posture, during no light touch condition, participants stood with their arms along the sides of the body. A similar approach was implemented previously [5]. Three trials lasting 30 s were conducted in each condition, the conditions were randomized for each subject.

Fig. 1. Experimental setup

2.4. Statistical analysis

Descriptive statistics are given as mean ± SD (normally distributed data) or as median (lower quartile-upper quartile) for non-normally distributed data. The time course of average changes in amplitude variables during the two occasions was analyzed using a paired t-test or a Wilcoxon signed-rank test. An α-level of $p < 0.05$ was accepted as statistically significant. To compare the influence of the plane and condition on the regularity level and amplitude parameters, a Wilcoxon signed-rank test or paired t-test with Bonferonni correction for multiply comparisons was applied ($p < 0.016$). Statistica software package (TIBCO Software, Inc., USA) version 13.1 for Windows was used for all statistical procedures. The standardized mean difference effect size for within-subjects designs were calculated (Cohen's d_z). Effect sizes were as follow: small ($d = 0.2$), medium ($d = 0.5$) and large ($d = 0.8$) [7].

3. Results

When standing with no light touch, the COP sway area was 2.196 ± 1.501 cm^2. The sway area reduced to 1.223 ± 1.061 cm^2 when the participants applied light touch to a stationary object. The difference between conditions was statistically significant ($Z = 3.96$, $p < 0.001$).

Similarly sway range ($t = 4.43$, $p < 0.001$), movement variability expressed by root mean square error ($t = 4.41$, $p < 0.001$) and COP velocity ($t = 3.19$, $p < 0.01$) decreased significantly in the anteroposterior direction, with medium to large effect, in the light touch condition when compared to NoLT. In the mediolateral direction, amplitude parameters did not change significantly between LT and NoLT (Table 1). During NoLT condition, the sway range, movement variability and COP velocity differed significantly between planes,

Table 1. Comparison of the postural sway parameters in the anteroposterior (AP) and mediolateral (ML) directions during quiet standing without (NoLT) and with additional light touch (LT)

Variable	Direction	NoLT	LT	*p*	Effect size
raCOP [cm]	AP	2.25 (0.79)	1.49 (0.63)	<0.001	0.79
	ML	1.372 (0.594)	1.210 (0.488)	0.07	0.33
AP versus ML		$p < 0.001$	$p = 0.002$		
rmseCOP [cm]	AP	0.47 (0.182)	0.291 (0.146)	<0.001	0.78
	ML	0.251 (0.117)	0.225 (0.098)	0.12	0.28
AP versus ML		$p < 0.001$	$p = 0.008$		
vCOP [cm/s]	AP	0.673 (0.191)	0.552 (0.195)	0.013	0.57
	ML	0.500 (0.213)	0.457 (0.185)	0.17	0.25
AP versus ML		$p < 0.001$	$p < 0.001$		
Area [cm^2]		2.196 (1.501) 1.57 (2.18)	1.223 (1.061) 0.93 (0.89)	<0.001	0.63

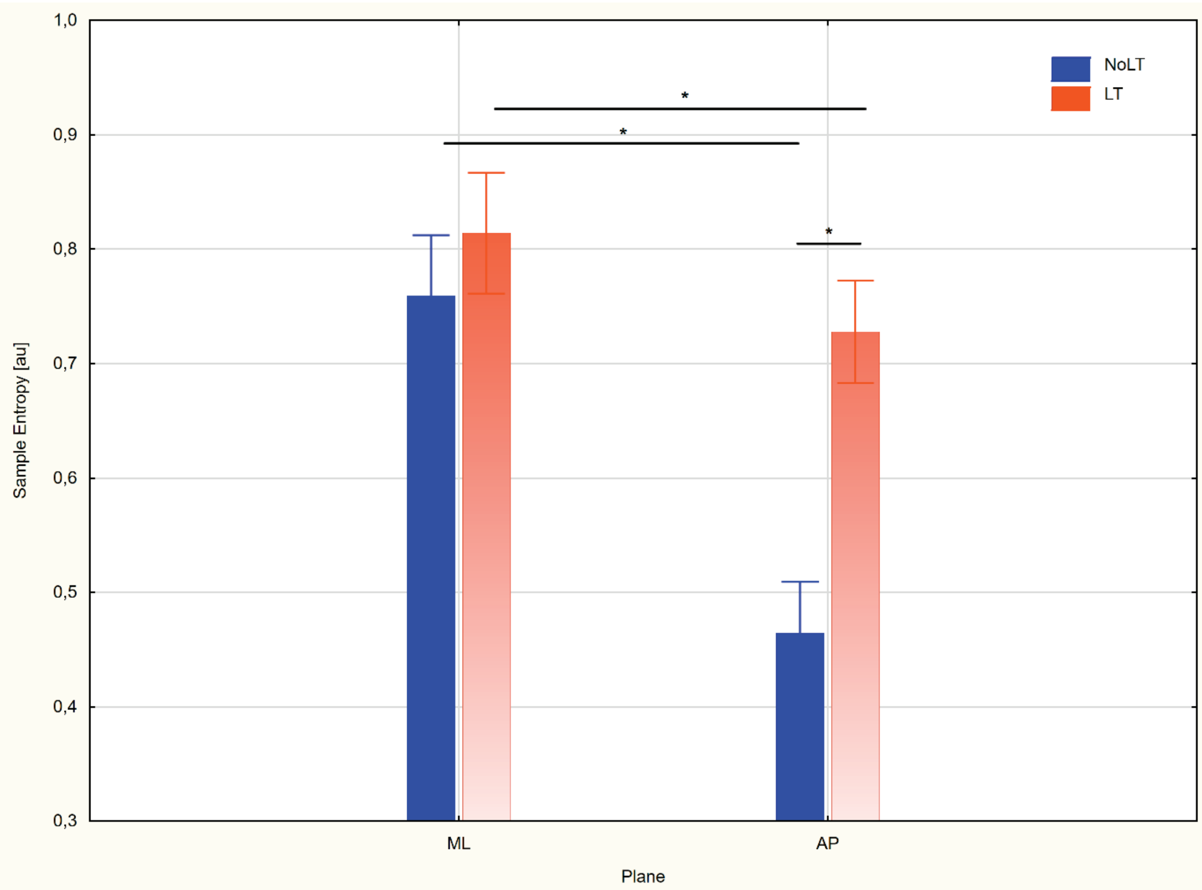

Fig. 2. The mean sample entropy during quiet standing with (LT) and without light touch (NoLT) in the anterior-posterior (AP) and medial-lateral (ML) directions. The error bars represent 95% confidence intervals of the mean; *$p < 0.016$

all these variables were higher in the anteroposterior direction (accordingly: $t = 7.77$, $d_z = 1.36$, $p < 0.001$; $t = 7.09$, $d_z = 1.25$, $p < 0.001$; $t = 6.87$, $p < 0.001$, $d_z = 1.21$). Similar differences were seen in the light touch condition (accordingly: $t = 3.37$, $p = 0.002$, $d_z = 0.59$; $t = 2.85$, $p = 0.008$, $d_z = 0.5$, $t = 4.30$, $p < 0.001$, $d_z = 0.76$), however the effect size was smaller.

The structure of the COP signal in the anteroposterior direction becomes more irregular in the light touch condition ($Z = 6.38$, $p < 0.001$) compared to quiet standing with no light touch, the effect size was large ($d_z = 0.79$). In the mediolateral direction the level of regularity did not change significantly ($Z = 1.62$, $p = 0.11$, $d_z = 0.26$). During quiet standing condition as well for the light touch condition, the irregularity level was significantly higher for the mediolateral direction (accordingly NoIT: $Z = 7.13$, $p < 0.001$ LT: $Z = 2.59$, $p = 0.009$) compared to anteroposterior direction, however, in the latter condition, the difference was much lower and the effect size was small ($d_z = 0.29$). Furthermore, the irregularity in the AP direction increased significantly in the light touch condition and reached the level of the irregularity in the ML direction without light touch. The conditions did not differ significantly ($Z = 0.81$, $p = 0.41$, $d_z = 0.09$).

The results are shown as the mean (SD) and median (IRQ); Wilcoxon signed-rank test or paired t-test with Bonferonni correction for multiply comparisons was applied ($p < 0.016$). The standardized mean difference effect size for within-subjects designs were calculated (Cohen's d_z), small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$).

4. Discussion

The goal of this study was to evaluate the influence of the additional tactile information (light fingertip touch) on the amount of sway and regularity of the COP signal in a group of healthy young adults during quiet standing task. Numerous studies concerning the influence of haptic cues on postural control during standing revealed that this additional source of information is useful in stabilizing posture. This effect is independent of age, vision condition or testing posture [1], [5], [6], [16], [25], but it is said to be related to the standing orientation [16]. Our results revealed that during side-by-side stance with additional touch information, participants substantially decreased the amount of sway in the anteroposterior direction, what was fully in line with our expectations and results obtained by previous authors [5], [6], [16], [17]. There are some discrepancies in the literature when it comes to the influence of the light touch on the mediolateral postural sway during side-by-side quiet standing. Some authors did not report results in frontal plane [17], [21], others decided not to analyze parameters in this plane [9], [16], another ones reported no significant effects in mediolateral direction [5] and the next ones described significant improvement of postural sway in both directions [17]. In the current experiment, participants revealed no significant influence of light touch on postural sway in the mediolateral direction in amplitude parameters. Our results are in line with those reported by Chen et al. [5]. In contrast, Lee et al. [17] reported decreased excursion with additional tactile information in ml direction, whereas, similarly to our results, velocity remained unchanged. The explanation for this discrepancy is that Lee at al. [17] reported values of excursion which were simply mean values of COP time series, while we evaluated range and variability (rms) of the COP. Furthermore, the authors did not report constant feet position on the platform, thus, it is unknown to what extent the reported changes are the result of additional feedback (light touch) or different feet position on the platform in subsequent measurements.

Consistently with previous results [8], [23], [32], during quiet standing, participants showed greater postural sway range, variability and movement velocity in the anterioposterior direction compared to mediolateral direction. Similarly, during the light touch condition, participants showed a greater amount of sway in the sagittal plane, however, these differences were smaller (smaller effect size) than without tactile information. Furthermore, with additional tactile information, the amount of sway in the sagittal plane decreased, so that it reached level of sway in the frontal plane without additional feedback. From the mechanical perspective, in the frontal plane, due to fewer degrees of freedom in closed kinetic chain, it is easier for the system to control center of gravity position than in open kinetic chain with more degrees of freedom in the sagittal plane. It suggests that in healthy adults, in side-by-side position, postural sway must be more controlled in the sagittal plane. The previous authors reported similar findings [8], [23].

The similar situation could be observed for the irregularity of the COP signal, which is said to express the level of "automatization" and/or attention devoted to posture [8], [23], [24]. The irregularity in the structure of the COP signal can be higher when the motor system is less constrained, when more components can interact with each other during controlling balance, it is often associated with higher efficiency and automaticity. Conversely, more attention devoted to postural control leads to decreased irregularity of the COP structure (lower SampEn) because movements become more constrained as a fewer components of the system can work together [4], [12], [20]. In the current experiment, during quiet standing, the SampEn was significantly higher in the mediolateral direction compared to anteroposterior direction, suggesting that participants in the frontal plane exhibited more automated behavior and/or devoted less attention to control posture. Vuillerme et al. [30] revealed that using tactile cues as a source of information to enhance postural control is processed which requires a certain amount of attention. Thus, we hypothesized that standing with additional cutaneous information diverts attention from posture, thereby bringing more irregular COP signal. That was indeed true, however, only in the sagittal plane thus our hypothesis was partially confirmed. The COP fluctuations in the frontal plane remained unaltered in the light touch condition. It suggests that in young, healthy adults during side-by-side standing postural control in this direction does not need much attention. Similar findings were reported by previous authors [8], [23]. Donker et al. [8] reported that increasing cognitive involvement in postural control induced by visual deprivation led to increased signal regularity only in the sagittal plane. It is interesting that, in the current experiment, during light touch condition the level of the COP regularity decreased in the sagittal plane and reached level in the frontal plane without LT. This again suggests that postural sway is mostly controlled in the sagittal plane and, according to the hypothesis proposed by Roerding et al. [23], that in the mediolateral direction the control is mostly automated. Control in frontal plane could not be more enhanced by LT adopted in the current study. Our results supported the notion that diverting attention from posture can modify postural control and lead to an increased irregularity of the COP signal [8], [12], [20].

5. Conclusions

There are some limitations in the current study. We evaluated only one light touch position, thus, we cannot state if different position of the upper limb (e.g., placed in a frontal plane) would not influence the mediolateral direction in side-by-side position. Also, as the current study evaluated only three trials in the light touch condition it is unknown how the stimuli would affect the system during repetitive measurements (i.e., in the learning or habituation process). Another limitation is that we did not evaluate the influence of light touch in the visual deprivation conditions. Thus, it is unknown whether similar results would be obtained when standing with eyes closed. Future studies are needed to assess possible effects of adaptation of the system to the additional tactile information as well as to evaluate the simultaneous influence of light touch and visual deprivation.

In conclusion, our results support the notion that the light fingertip touch provides additional information which enhances postural stabilization. Also, it leads to increased COP irregularity in the sagittal plane without influence on the frontal plane in healthy young adults. Nonlinear measures of signal regularity (i.e., SampEn) provides surplus insight into the human postural control and can be used as an additional useful tool to traditional balance measures.

References

[1] BARELA A.M.F., CAPORICCI S., DE FREITAS P.B., JEKA J.J., BARELA J.A., *Light touch compensates peripheral somatosensory degradation in postural control of older adults*, Hum. Mov. Sci., 2018, 60, 122–130. https://doi.org/10.1016/j.humov.2018.06.001

[2] BECKER K.A., HUNG C.J., *Attentional focus influences sample entropy in a balancing task*, Hum. Mov. Sci., 2020, 72, 102631, https://doi.org/10.1016/j.humov.2020.102631

[3] BUSA M.A., VAN EMMERIK R.E.A., *Multiscale entropy: A tool for understanding the complexity of postural control*, J. Sport Heal. Sci., 2016, 5, 44–51, https://doi.org/10.1016/j.jshs.2016.01.018

[4] CAVANAUGH J.T., MERCER V.S., STERGIOU N., *Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: A methodological report*, J. Neuroeng. Rehabil., 2007, 4, 1–7, https://doi.org/10.1186/1743-0003-4-42

[5] CHEN F.C., CHEN H.L., TU J.H., TSAI C.L., *Effects of light touch on postural sway and visual search accuracy: A test of functional integration and resource competition hypotheses*, Gait Posture, 2015, 42, 280–284, https://doi.org/10.1016/j.gaitpost.2015.06.001

[6] CHEN F.C., TSAI C.L., *The mechanisms of the effect of light finger touch on postural control*, Neurosci. Lett., 2015, 605, 69–73, https://doi.org/10.1016/j.neulet.2015.08.016

[7] COHEN J., *Statistical Power Analysis for the Behavioral Sciences*, NY Routledge Acad., New York, 1988.

[8] DONKER S.F., ROERDINK M., GREVEN A.J., BEEK P.J., *Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control*, Exp. Brain Res., 2007, 181, 1–11, https://doi.org/10.1007/s00221-007-0905-4

[9] DOS SANTOS D.G., PRADO-RICO J.M., ALOUCHE S.R., GARBUS R.B. DE S.C., DE FREITAS P.B., DE FREITAS S.M.S.F., *Combined effects of the light touch and cognitive task affect the components of postural sway*, Neurosci. Lett., 2019, 703, 99–103, https://doi.org/10.1016/j.neulet.2019.03.027

[10] HANSEN C., WEI Q., SHIEH J.S., FOURCADE P., ISABLEU B., MAJED L., *Sample entropy, univariate and multivariate multiscale entropy in comparison with classical postural sway parameters in young healthy adults*, Front. Hum. Neurosci., 2017, 11, https://doi.org/10.3389/fnhum.2017.00206

[11] JEKA J.J., LACKNER J.R., *Fingertip contact influences human postural control*, Exp. Brain Res., 1994, 79, 495–502, https://doi.org/10.1007/BF00229188

[12] KEE Y.H., CHATZISARANTIS N.N.L.D., KONG P.W., *Mindfulness, Movement Control and Attentional Focus Strategies: Effects of Mindfulness on a Postural Balance Task*, 2012, 561–579.

[13] LAJOIE Y., TEASDALE N., BARD C., FLEURY M., *Upright Standing and Gait: Are There Changes in Attentional Requirements Related to Normal Aging?*, Exp. Aging Res., 1996, 22, 185–198, https://doi.org/10.1080/03610739608254006

[14] LAJOIE Y., TEASDALE N., BARD C., FLEURY M., *Attentional demands for static and dynamic equilibrium*, Exp. Brain Res., 1993, 97, 139–144, https://doi.org/10.1007/BF00228824

[15] LAKE D.E., RICHMAN J.S., GRIFFIN P.M., RANDALL MOORMAN J., *Sample entropy analysis of neonatal heart rate variability*, Am. J. Physiol. – Regul. Integr. Comp. Physiol., 2002, 283, https://doi.org/10.1152/ajpregu.00069.2002

[16] LEE I.C., PACHECO M.M., NEWELL K.M., *Postural coordination and control to the precision demands of light finger touch*, Exp. Brain Res., 2019, 0, 0, https://doi.org/10.1007/s00221-019-05513-2

[17] LEE Y., GOYAL N., ARUIN A.S., *Effect of a cognitive task and light finger touch on standing balance in healthy adults*, Exp. Brain Res., 2018, 236, 399–407, https://doi.org/10.1007/s00221-017-5135-9

[18] LUBETZKY A.V., HAREL D., LUBETZKY E., *On the effects of signal processing on sample entropy for postural control*, PLoS One, 2018, 13, 1–15, https://doi.org/10.1371/journal.pone.0193460

[19] PETERKA R.J., GOODWORTH A.D., MELLODGE P., PETERKA R.J., VOLPE D., GIANTIN M.G., MAESTRI R., FRAZZITTA G., REHABIL C., HONEYCUTT C.F., NICHOLS T.R., *Sensorimotor Integration in Human Postural Control*, J. Neurophysiol., 2002, 1097–1118.

[20] RHEA C.K., DIEKFUSS J.A., FAIRBROTHER J.T., RAISBECK L.D., *Postural control entropy is increased when adopting an external focus of attention*, Motor Control, 2019, 23, 230–242, https://doi.org/10.1123/mc.2017-0089

[21] RILEY M.A., STOFFREGEN T.A., GROCKI M.J., TURVEY M.T., *Postural stabilization for the control of touching*, Hum. Mov. Sci., 1999, 18, 795–817, https://doi.org/10.1016/S0167-9457(99)00041-X

[22] RILEY M.A., WONG S., MITRA S., TURVEY M.T., *Common effects of touch and vision on postural parameters*, Exp. Brain Res., 1997, 117, 165–170, https://doi.org/10.1007/s002210050211

[23] ROERDINK M., DE HAART M., DAFFERTSHOFER A., DONKER S.F., GEURTS A.C.H., BEEK P.J., *Dynamical structure of center-of--pressure trajectories in patients recovering from stroke*, Exp. Brain Res., 2006, 174, 256–269, https://doi.org/10.1007/s00221-006-0441-7

[24] ROERDINK M., HLAVACKOVA P., VUILLERME N., *Center-of--pressure regularity as a marker for attentional investment in postural control: A comparison between sitting and standing postures*, Hum. Mov. Sci., 2011, 30, 203–212, https://doi.org/10.1016/j.humov.2010.04.005

[25] SHIN S., MILOSEVIC M., CHUNG C. MIN, LEE Y., *Contractile properties of superficial skeletal muscle affect postural control in healthy young adults: A test of the rambling and trembling hypothesis*, PLoS One, 2019, 14, 1–18, https://doi.org/10.1371/journal.pone.0223850

[26] STERGIOU N., *Nonlinear Analysis for Human Movement Variability*, CRC Press Taylor & Francis Group, New York, 2016.

[27] STINS J.F., MICHIELSEN M.E., ROERDINK M., BEEK P.J., *Sway regularity reflects attentional involvement in postural control: Effects of expertise, vision and cognition*, Gait Posture, 2009, 30, 106–109, https://doi.org/10.1016/j.gaitpost.2009.04.001

[28] TEASDALE N., SIMONEAU M., *Attentional demands for postural control: The effects of aging and sensory reintegration*, Gait Posture, 2001, 14, 203–210, https://doi.org/10.1016/S0966-6362(01)00134-5

[29] VUILLERME N., DANION F., MARIN L., BOYADJIAN A., PRIEUR J.M., WEISE I., NOUGIER V., *The effect of expertise in gymnastics on postural control*, Neurosience Lett., 2001, 303, 83–86.

[30] VUILLERME N., ISABLEU B., NOUGIER V., *Attentional demands associated with the use of a light fingertip touch for postural control during quiet standing*, 2006, 232–236, https://doi.org/10.1007/s00221-005-0142-7

[31] VUILLERME N., NOUGIER V., *Attentional demand for regulating postural sway: The effect of expertise in gymnastics*, Brain Res. Bull., 2004, 63, 161–165, https://doi.org/10.1016/j.brainresbull.2004.02.006

[32] WINTER D.A., PRINCE F., FRANK J.S., POWELL C., ZABJEK K.F., *Unified theory regarding A/P and M/L balance in quiet stance*, J. Neurophysiol., 1996, 75, 2334–2343, https://doi.org/10.1152/jn.1996.75.6.2334

[33] WOOLLACOTT M., SHUMWAY-COOK A., *Attention and the control of posture and gait: A review of an emerging area of research*, Gait Posture, 2002, 16, 1–14, https://doi.org/10.1016/S0966-6362(01)00156-4