Acta of Bioengineering and Biomechanics
Vol. 21, No. 3, 2019

Original paper
DOI: 10.5277/ABB-01390-2019-02

Effect of sound on standing postural stability in the elderly with and without knee osteoarthritis

PICHAYA HENGSOMBOON[1], VIMONWAN HIENGKAEW[1],
WEI-LI HSU[2], SUNEE BOVONSUNTHONCHAI[1]*

[1] Faculty of Physical Therapy, Mahidol University, Nakhon Pathom, Thailand.
[2] School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, Taipei, Taiwan.

Purpose: The aim of the study was to investigate the influence of sound on standing postural control in the elderly with and without knee osteoarthritis (knee-OA). *Methods*: Twenty-six elderly with knee-OA and 26 elderly without knee-OA who matched the age and height participated in this study. The standing postural stability was assessed by the 3D motion analysis system. Four testing conditions of the combination of sound (no sound and white noise sound) and surface (firm and soft surfaces) were tested three times with eyes closed for 30 sec. Postural stability variables included the standard deviation and velocity of the centre of pressure, the total body centre of mass, and centre of the head along the antero-posterior (AP) and medio-lateral (ML) directions. *Results*: Statistical significant reductions of all variables along ML direction were found in the elderly without a knee-OA in the presence of sound during standing on a firm surface. No significant effect of sound was found in the elderly with the knee-OA during standing on a firm surface. In the standing on a soft surface, both groups demonstrated no significant effect of sound on all postural stability variables. *Conclusions*: Application of sound improved the standing postural stability in the frontal plane for the elderly without knee-OA. However, the effect of sound was limited in standing on a soft surface for both elderly with and without knee-OA.

Key words: *ageing, auditory, balance, knee osteoarthritis, sensory reweighting*

1. Introduction

Normal postural stability requires the feedback information from at least three primary sensory systems including the visual, vestibular, and somatosensory systems [10]. All feedbacks are used to determine the state of body and surrounding environment which is important for controlling the stable posture [10]. Impairment of the feedback systems can result in poor control of posture and increase of postural sway. The previous study reported a significant increase of postural sway in participants with profound vision loss [26], vestibulopathy [8], and peripheral neuropathy of lower extremity [30]. Moreover, declining of all feedback systems, which is naturally found in the elderly, can result in the reduction of postural stability [25], [28].

Beside the three primary feedback systems, the auditory system also contributes to stabilizing posture, especially when the other feedback systems are impaired [6], [7] or limited [9], [15], [31]. The study of Easton et al. [7] demonstrated that blind individuals could use sound to reduce their body and head sway in the lateral direction. They explained that the sound provided a spatial reference for posture maintaining. Central nervous system could detect the changes of distance and direction of the sound sources and interpret as body and head sway instead of using vision. Dozza et al. [6] reported the effectiveness of sound on postural stability in bilateral vestibular loss participants. They also reported more enhancement of postural stability when applying the sound in the condition of limited other feedback systems. This enhancing effect of the sound might be explained by the sensory re-weighting mechanism [23]. In addition, it had been confirmed by

* Corresponding author: Sunee Bovonsunthonchai, Faculty of Physical Therapy, Mahidol University, 999 Phuttamonthon 4 Road, Salaya, Nakhon Pathom 73170, Thailand. E-mail: sunee.bov@mahidol.edu
Received: May 27th, 2019
Accepted for publication: July 22nd, 2019

the studies of Zhong and Yost [31], Gandemer et al. [9], and Karim et al. [15] that sound can be used as the spatial reference or auditory landmark to maintain postural stability in healthy participants when the visual system was limited. The potential of sound to increase postural stability in the limiting of somatosensory input was investigated in the previous study [9]. The study investigated the effect of sound on postural stability during standing on a soft surface (decreased somatosensory input from feet) in young participants. However, no significant effect of sound was found in this study. This might be explained by the insufficient reduction of somatosensory input by using the soft (foam) surface for the young participants.

According to the ageing process, the elderly have poorer postural stability than the young due to the decrement of all feedback information. From the comparative study of standing balance between healthy young adults and elderly, greater lateral body sway was found in the elderly when moving the sound source laterally [29]. Following the reweighting mechanism concept, the sound is probably useful to improve stability for the elderly better than the young. From the reviews, it was clear that the sound cue had the potential to be used as the augmented feedback to improve postural stability in the limited visual and vestibular systems. However, little is known about the effect of sound on postural stability among participants with an impaired or limited somatosensory feedback system, which includes the exteroception (touch and pressure) and proprioception (muscles and joints senses). In order to disturb the exteroception and proprioception in the postural stability testing, the soft surface (standing on foam) can be used as the constrained condition [22]. Moreover, it may be more proper to study in participants with known impaired lower extremity proprioception who have problem of balance as the knee osteoarthritis (OA) [16]. It could provide more information about the auditory contributions in the standing postural stability. Thus, the study aimed to investigate the effect of sound on the postural stability during standing on firm and soft surfaces in elderly participants both with and without knee OA. The hypothesis of the study was that elderly with and without knee-OA demonstrated a more stable stance when they listened to the sound during standing on both types of stance surface.

2. Materials and methods

This study used the comparative experimental study design to investigate the effect of sound on the standing postural control in the elderly with and without knee-OA. The study's protocol was approved by the Institutional Review Board (MU-CIRB 2017/095.2205). All participants were informed about the procedure of study and signed the consent form prior to participation in the study.

2.1. Participants

Seventy-three elderly volunteers with and without knee-OA were recruited by the convenience sampling method from the Physical Therapy Centre, Faculty of Physical Therapy, Mahidol University, and from the local community during November 2017 to November 2018. The elderly with knee-OA were recruited if they had unilateral or bilateral knee-OA that followed the criteria of the American College of Rheumatology (ACR) [14] and mild to moderate severity level defined by the index of severity for knee diseases (ISK) [19]. The elderly with normal findings of both knees with matched the age and height were recruited as the elderly without knee-OA group. Participants were screened by the orthopaedics physical therapists with experience in the musculoskeletal field for more than 5 years.

Participants with neurological problems, musculoskeletal disease (excepted knee-OA in the elderly with knee-OA group), history of spine or lower limb surgery, diabetes mellitus, visual problem that cannot be corrected by lens, dizziness or vertigo, history of fall within 12 months prior testing, inability to standing or walking independently were excluded from the study. Participants' hearing function was screened using the whispered voice test [24]. They were excluded if they had positive results. Also, participants with mild cognitive impairment (determined by the Montreal Cognitive Assessment (MoCA) (XXX version), scores less than 25 points) [21] were excluded.

2.2. Experimental setup

To investigate the effect of sound on postural stability of participants, the study used the 10 high-speed infrared cameras (Vicon^{TM}, Vantage V5, UK) and a force plate (AMTI model OR6-7, USA), which were installed in the quiet laboratory room. The sampling frequency of the camera and force plate were set at 100 Hz and 1 kHz, respectively. The workstation personal computer with Nexus version 2.7 software was used to determine the postural sway data.

Before data collection, the researcher placed 35 spherical retro-reflexive markers (14 mm in diameter) on the participants' body prominence following the full-body Plug-In Gait (PIG) model [3]. To provide the static sound sources during testing, the wide-band white noise sound (WNS; 20 to 20,000 Hz), which was generated by the customized software, was launched from 2 loudspeakers. The loudspeakers were placed beside both participant's ears with 1 meter away. During the test in sound condition, the participant was asked to listen and count the number of hearing. The number of sounds was random (5, 6, or 8 times for each trial). In the no sound condition, participants were asked to wear the earmuffs model 3M Optime™ 105 during the test. These earmuffs could reduce 30 decibels of sound intensity, which enables to eliminate ambient sound in the testing room. In the soft surface condition, this study used thermoplastic elastomer (TPE) foam pad with the size 40 × 50 × 6.5 cm (width × length × height). For the firm surface condition, participants stood directly on the force plate. The flow chart of the present study is shown in Fig. 1.

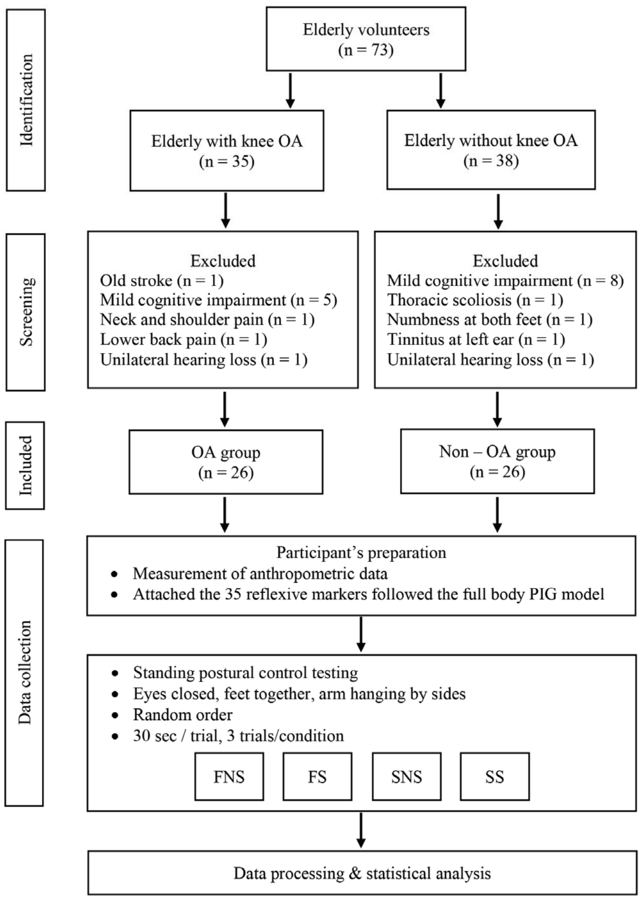


Fig. 1. The flowchart of the present study

To eliminate the other confounding factors that may exist over days, different conditions of testing were collected within a day for each participant. The 2 factors of testing condition composed of sound (no sound/sound) and surface (firm/soft) were launched randomly. The total 4 testing conditions for the study were included: 1) firm surface + no sound (FNS), 2) firm surface + sound (FS), 3) soft surface + no sound (SNS), and 4) soft surface + sound (SS).

2.3. Testing procedures

Standing postural control of the participants was tested in 4 above-mentioned conditions. During testing, the subjects were asked to stand as still as possible with eyes-closed, bare feet, feet together, and arms hanging by sides. The testing procedures for this study followed the previous study protocol that reported the high reliability of postural variables testing [17]. In order to prevent the effect of muscular fatigue and discomfort during testing, each condition was repeated three times for 30 seconds. Participants were allowed rest between trials if needed. Besides, a one-minute resting period was set between the testing conditions. In addition, we used the data from the last 2 successful trials for further processing and analysis to avoid the unfamiliar with the testing method in the first trial.

2.4. Outcome measures

Postural control variables for this study included the standard deviation of center of pressure (COP) along the antero-posterior (AP) ($SDCOP_{AP}$) and medio-lateral (ML) ($SDCOP_{ML}$) directions, standard deviation of total body center of mass (TBCM) along AP ($SDTBCM_{AP}$) and ML ($SDTBCM_{ML}$) directions, standard deviation of center of head (COH) along AP ($SDCOH_{AP}$) and ML ($SDCOH_{ML}$) directions, velocity of COP along AP ($VCOP_{AP}$) and ML ($VCOP_{ML}$) directions, velocity of TBCM along AP ($VTBCM_{AP}$) and ML ($VTBCM_{ML}$) directions, and velocity of COH along AP ($VCOH_{AP}$) and ML ($VCOH_{ML}$) directions.

2.5. Data analysis

Postural control variables were calculated from the mid-10 seconds of the total 30 seconds. Cut-off frequency for trajectory data and COP data were 3 and 10 Hz, respectively. Both trajectory and COP data were exported as an American Standard Code for Information Interchange (ASCII) file type. All

ASCII files were imported to the Matlab software released R2013a (license number 891627) for calculation of all postural control variables. COP variables were calculated from COP data from the force plate, while TBCM and COH variables were calculated from trajectory data. The sway velocity and standard deviation of all variables were calculated following the formulas which were described in the previous study [5].

The Kolmogorov–Smirnov Goodness of Fit test was used to test the data distribution and showed normally distributed. The 2-way mixed model analysis of variance (ANOVA) was used to analyze the main effects of group (between group) and conditions (within group), and potential interaction between group and conditions for all variables. The independent *t*-test was performed to compare the postural control variables between elderly with and without knee-OA groups. The one-way repeated measure ANOVA was undertaken to find the differences in the postural control variables between conditions within the same group. If the significant results of the one-way repeated measure ANOVA were found, the Bonferroni test was used for the pairwise comparison to find different pairs of conditions within the same group. All statistical significance level was set at $p < 0.05$. All analyses were performed using the Statistical Package for Social Sciences (SPSS version 23.0).

2.6. Sample size estimation

This study estimated sample size from our own pilot data ($n = 10$) on the comparison of $VCOP_{ML}$ between SNS and SS conditions in elderly without knee-OA group. The data showed means and standard deviations of $VCOP_{ML}$ in SNS and SS conditions were 46.34 ± 28.38 and 38.79 ± 13.86, respectively. By using the G*Power program version 3.1.9.2, the function of the *t*-test, matched pairs and a priori was selected. The alpha error and power were set as 0.05 and 0.8, respectively. The estimated number of the total sample was 45. Therefore, data collection from 52 participants in the present study was sufficient to answer the research question.

3. Results

Finally, 52 elderly participated in the study and were classified into the elderly with ($n = 26$) and without knee-OA ($n = 26$) groups, participated in the study. Characteristics of the participants in both groups are presented in Table 1. Comparisons of the demographic data showed no significant differences ($p > 0.05$) for age, gender, weight, height, leg length, and MoCA.

Table 1. Characteristics of the elderly with ($n = 26$) and without ($n = 26$) knee-OA

Variables	With knee OA Mean ± SD or *n* (%)	Without knee OA Mean ± SD or *n* (%)	*p*-value
Age [years]	65.38±3.60	64.50±3.11	0.348[a]
Gender Male Female	 2 (7.69%) 24 (92.31%)	 8 (30.77 %) 18 (69.23 %)	0.070[b]
Weight [kg]	61.47 ± 9.36	58.07±11.76	0.253[a]
Height [cm]	155.50 ± 7.57	156.79±8.35	0.564[a]
Body mass index [kg/m^2]	25.35 ± 2.85	23.48±3.48	0.039[a]
Leg length [cm] Left Right	 80.31 ± 4.50 80.29 ± 4.56	 80.56±4.72 80.62±4.81	 0.834[a] 0.802[a]
MoCA score	27.23 ± 1.61	27.96±1.46	0.092[a]
Affected side Left Right Both	 5 (19.23%) 6 (23.08%) 15 (57.69%)	n/a	n/a
Knee pain, VAS [cm]	3.73 ± 1.31	n/a	n/a
ISK [scores]	5.42 ± 1.54	n/a	n/a
Duration of symptom [years]	4.53 ± 3.92	n/a	n/a

MoCA: Montreal Cognitive Assessment, VAS: visual analogue scale, ISK: index of severity for knee disease, n/a: not applicable.

[a] Independent *t*-test, [b] Chi-Square test, the significant level was set at $p < 0.05$.

For the elderly with knee-OA, they had mild knee pain with the mean VAS score of 3.73 cm [11], moderate severity of OA at the knee grading by the ISK [19], and the mean duration of the symptom of 4.53 years. The elderly without knee-OA had no pain or other clinical symptoms at the knee.

The maximum voluntary isometric contraction (MVIC) of hip, knee, and ankle muscles of both legs were measured for all participants. The measurement of MVIC was done by using the handheld dynamometer (Lafayette Manual Muscle Tester, Model #01163) following the previous testing protocol for the elderly [1]. The MVIC test was done by the trained researcher (Hengsomboon, P.) with a high test-retest reliability ($ICC_{3,\ 1}$ = 0.98). Results of the comparisons of MVIC of lower extremity between elderly with (*n* = 26) and without (*n* = 26) knee-OA are presented in Table 2. The MVIC results demonstrate no significant differences of MVIC of all muscle groups between averaged both sides (for the elderly without knee-OA), affected, and unaffected sides (for elderly with knee-OA).

There were significant main effect of condition for all testing variables including the $SDCOP_{AP}$ [$F_{(2.121, 106.064)} = 187.210$, $p < 0.001$, $\eta^2 = 0.789$], $SDCOP_{ML}$ [$F_{(2.500, 125.016)} = 161.999$, $p < 0.001$, $\eta^2 = 0.764$], $SDTBCM_{AP}$ [$F_{(2.255, 112.766)} = 146.127$, $p < 0.001$, $\eta^2 = 0.745$], $SDTBCM_{ML}$ [$F_{(2.615, 130.762)} = 94.993$, $p < 0.001$, $\eta^2 = 0.655$], $SDCOH_{AP}$ [$F_{(2.314, 115.700)} = 116.775$, $p < 0.001$, $\eta^2 = 0.700$], $SDCOH_{ML}$ [$F_{(2.549, 127.462)} = 74.619$, $p < 0.001$, $\eta^2 = 0.599$], $VCOP_{AP}$ [$F_{(1.818, 90.906)} = 107.195$, $p < 0.001$, $\eta^2 = 0.682$], $VCOP_{ML}$ [$F_{(1.835, 91.730)} = 118.820$, $p < 0.001$, $\eta^2 = 0.704$], $VTBCM_{AP}$ [$F_{(2.027, 101.347)} = 232.451$, $p < 0.001$, $\eta^2 = 0.823$], $VTBCM_{ML}$ [$F_{(2.263, 113.156)} = 179.192$, $p < 0.001$, $\eta^2 = 0.782$], $VCOH_{AP}$ [$F_{(2.101, 105.041)} = 177.239$, $p < 0.001$, $\eta^2 = 0.680$], and $VCOH_{ML}$ [$F_{(2.003, 100.130)} = 106.225$, $p < 0.001$, $\eta^2 = 0.780$].

No significant main effect of group was found in the study for $SDCOP_{AP}$ [$F_{(1, 50)} = 2.253$, $p = 0.140$, $\eta^2 = 0.043$], $SDCOP_{ML}$ [$F_{(1, 50)} = 0.641$, $p = 0.427$, $\eta^2 = 0.013$], $SDTBCM_{AP}$ [$F_{(1, 50)} = 0.706$, $p = 0.405$, $\eta^2 = 0.014$], $SDTBCM_{ML}$ [$F_{(1, 50)} = 0.262$, $p = 0.611$, $\eta^2 = 0.005$], $SDCOH_{AP}$ [$F_{(1, 50)} = 0.577$, $p = 0.451$, $\eta^2 = 0.011$], $SDCOH_{ML}$ [$F_{(1, 50)} = 0.132$, $p = 0.718$, $\eta^2 = 0.003$], $VCOP_{AP}$ [$F_{(1, 50)} = 0.023$, $p = 0.880$, $\eta^2 = 0.000$], $VCOP_{ML}$ [$F_{(1, 50)} = 1.420$, $p = 0.239$, $\eta^2 = 0.028$], $VTBCM_{AP}$ [$F_{(1, 50)} = 0.931$, $p = 0.339$, $\eta^2 = 0.018$], $VTBCM_{ML}$ [$F_{(1, 50)} = 0.000$, $p = 0.989$, $\eta^2 = 0.000$], $VCOH_{AP}$ [$F_{(1, 50)} = 1.116$, $p = 0.296$, $\eta^2 = 0.022$], and $VCOH_{ML}$ [$F_{(1, 50)} = 0.377$, $p = 0.542$, $\eta^2 = 0.007$].

There was no significant interaction effect between group and condition for $SDCOP_{AP}$ [$F_{(2.121, 106.064)} = 0.709$, $p = 0.502$, $\eta^2 = 0.014$], $SDCOP_{ML}$ [$F_{(2.500, 125.016)} = 0.972$, $p = 0.397$, $\eta^2 = 0.019$], $SDTBCM_{AP}$ [$F_{(2.255, 112.766)} = 0.526$, $p = 0.614$, $\eta^2 = 0.010$], $SDTBCM_{ML}$ [$F_{(2.615, 130.762)} = 1.277$, $p = 0.285$, $\eta^2 = 0.025$], $SDCOH_{AP}$ [$F_{(2.314, 115.700)} = 0.244$, $p = 0.815$, $\eta^2 = 0.005$], $SDCOH_{ML}$ [$F_{(2.549, 127.462)} = 1.322$, $p = 0.271$, $\eta^2 = 0.026$], $VCOP_{AP}$ [$F_{(1.818, 90.906)} = 0.061$, $p = 0.927$, $\eta^2 = 0.001$], $VCOP_{ML}$ [$F_{(1.835, 91.730)} = 0.123$, $p = 0.868$, $\eta^2 = 0.002$], $VTBCM_{AP}$ [$F_{(2.027, 101.347)} = 0.352$, $p = 0.707$, $\eta^2 = 0.007$], $VTBCM_{ML}$ [$F_{(2.263, 113.156)} = 0.894$, $p = 0.423$, $\eta^2 = 0.018$], $VCOH_{AP}$ [$F_{(2.003, 100.130)} = 0.350$, $p = 0.716$, $\eta^2 = 0.007$], and $VCOH_{ML}$ [$F_{(2.101, 105.041)} = 1.249$, $p = 0.291$, $\eta^2 = 0.024$].

Among the elderly without knee-OA group, the results of the repeated measure ANOVA demonstrated significant differences of all variables including the $SDCOP_{AP}$ [$F_{(1.723, 43.079)} = 83.776$, $p < 0.001$, $\eta^2 = 0.770$], $SDCOP_{ML}$ [$F_{(1.946, 48.655)} = 79.342$, $p < 0.001$, $\eta^2 = 0.760$], $SDTBCM_{AP}$ [$F_{(1.836, 45.910)} = 71.365$, $p < 0.001$,

Table 2. Comparisons of the maximum voluntary isometric contraction (MVIC) between the elderly with (*n* = 26) and without (*n* = 26) knee-OA

Muscle groups	With knee OA		Without knee OA	*p*-value*
	Affected side mean ± SD	Unaffected side mean ± SD	Averaged mean ± SD	
Hip				
Flexor	21.04 ± 4.62	21.21 ± 4.96	21.51 ± 3.36	0.927
Extensor	23.10 ± 4.17	24.06 ± 4.88	23.89 ± 3.70	0.687
Abductor	19.84 ± 3.75	21.06 ± 4.80	22.06 ± 4.58	0.197
Adductor	20.51 ± 3.65	20.55 ± 3.57	22.39 ± 3.03	0.085
Knee				
Flexor	18.21 ± 4.22	19.48 ± 4.40	20.62 ± 3.22	0.099
Extensor	22.42 ± 5.71	24.57 ± 5.39	25.09 ± 3.84	0.137
Ankle				
Dorsiflexor	22.52 ± 3.19	22.67 ± 3.12	23.09 ± 3.10	0.794
Plantarflexor	31.16 ± 5.05	31.74 ± 5.34	33.01 ± 4.91	0.411

* One-way ANOVA, the significant level was set at $p < 0.05$.

$\eta^2 = 0.741$], SDTBCM$_{ML}$ [$F_{(3, 75)} = 41.171$, $p < 0.001$, $\eta^2 = 0.622$], SDCOH$_{AP}$ [$F_{(1.995, 52.109)} = 55.162$, $p < 0.001$, $\eta^2 = 0.688$], SDCOH$_{ML}$ [$F_{(2.221, 55.535)} = 35.552$, $p < 0.001$, $\eta^2 = 0.587$], VCOP$_{AP}$ [$F_{(1.624, 40.588)} = 35.074$, $p < 0.001$, $\eta^2 = 0.584$], VCOP$_{ML}$ [$F_{(1.562, 39.039)} = 42.452$, $p < 0.001$, $\eta^2 = 0.629$], VTBCM$_{AP}$ [$F_{(1.745, 43.632)} = 114.867$, $p < 0.001$, $\eta^2 = 0.821$], VTBCM$_{ML}$ [$F_{(1.881, 47.019)} = 94.312$, $p < 0.001$, $\eta^2 = 0.790$], VCOH$_{AP}$ [$F_{(1.844, 46.101)} = 81.844$, $p < 0.001$, $\eta^2 = 0.766$], and VCOH$_{ML}$ [$F_{(1.765, 44.121)} = 82.484$, $p < 0.001$, $\eta^2 = 0.767$].

For the elderly with knee-OA group, the results of repeated measure ANOVA demonstrated significant differences of all variables including the SDCOP$_{AP}$ [$F_{(2.405, 60.134)} = 104.237$, $p < 0.001$, $\eta^2 = 0.807$], SDCOP$_{ML}$ [$F_{(2.004, 50.109)} = 83.287$, $p < 0.001$, $\eta^2 = 0.769$], SDTBCM$_{AP}$ [$F_{(2.291, 57.275)} = 75.259$, $p < 0.001$,

Table 3. Postural control variables of the elderly with ($n = 26$) and without ($n = 26$) knee-OA along the antero-posterior (AP) direction

Variables	Elderly with knee OA Mean ± SD				Elderly without knee OA Mean ± SD				*p*-value			
	FNS	FS	SNS	SS	FNS	FS	SNS	SS				
SDCOP$_{AP}$	4.83 ± 1.49	4.87 ± 2.30	12.16 ± 3.26	11.03 ± 2.86	4.44 ± 1.68	4.04 ± 1.79	10.66 ± 4.44	9.99 ± 3.43	0.379[a]	0.150[b]	0.173[c]	0.242[d]
	$F_{(2.405, 60.134)} = 104.237$, $p < 0.001$, $\eta^2 = 0.807$				**$F_{(1.723, 43.079)} = 83.776$, $p < 0.001$, $\eta^2 = 0.770$**							
VCOP$_{AP}$	13.80 ± 4.63	12.62 ± 4.81	36.18 ± 10.19	33.77 ± 10.41	12.74 ± 5.44	12.13 ± 6.66	36.60 ± 24.03	33.30 ± 17.22	0.452[a]	0.765[b]	0.935[c]	0.905[d]
	$F_{(2.136, 53.405)} = 124.110$, $p < 0.001$, $\eta^2 = 0.832$				**$F_{(1.624, 40.588)} = 35.074$, $p < 0.001$, $\eta^2 = 0.584$**							
SDTBCM$_{AP}$	3.78 ± 1.26	4.00 ± 1.97	8.23 ± 2.15	7.49 ± 1.91	3.78 ± 1.19	3.49 ± 1.43	7.66 ± 2.32	7.31 ± 1.72	0.888[a]	0.120[b]	0.544[c]	0.352[d]
	$F_{(2.291, 57.275)} = 75.259$, $p < 0.001$, $\eta^2 = 0.751$				**$F_{(1.836, 45.910)} = 71.365$, $p < 0.001$, $\eta^2 = 0.741$**							
VTBCM$_{AP}$	4.35 ± 1.35	4.50 ± 1.51	12.32 ± 3.58	11.39 ± 3.40	4.30 ± 1.20	3.87 ± 1.35	11.67 ± 4.04	10.60 ± 2.62	0.997[a]	0.283[b]	0.366[c]	0.733[d]
	$F_{(2.181, 54.526)} = 117.827$, $p < 0.001$, $\eta^2 = 0.825$				**$F_{(1.745, 43.632)} = 114.867$, $p < 0.001$, $\eta^2 = 0.821$**							
SDCOH$_{AP}$	6.97 ± 2.41	7.26 ± 3.30	13.43 ± 3.52	12.31 ± 3.36	6.66 ± 1.89	6.63 ± 2.45	12.58 ± 3.68	12.14 ± 3.03	0.609[a]	0.441[b]	0.401[c]	0.844[d]
	$F_{(3, 75)} = 62.162$, $p < 0.001$, $\eta^2 = 0.713$				**$F_{(1.995, 52.109)} = 55.162$, $p < 0.001$, $\eta^2 = 0.688$**							
VCOH$_{AP}$	8.12 ± 2.15	7.50 ± 2.41	18.33 ± 6.56	16.73 ± 4.52	8.37 ± 2.53	8.55 ± 2.84	19.59 ± 5.65	18.14 ± 5.63	0.707[a]	0.157[b]	0.459[c]	0.325[d]
	$F_{(2.226, 55.638)} = 95.937$, $p < 0.001$, $\eta^2 = 0.793$				**$F_{(1.844, 46.101)} = 81.844$, $p < 0.001$, $\eta^2 = 0.766$**							

VCOP$_{AP}$ – velocity of center of pressure along AP direction, SDCOP$_{AP}$ – standard deviation of center of pressure along AP direction, VTBCM$_{AP}$ – velocity of total body center of mass along AP direction, SDTBCM$_{AP}$ – standard deviation of total body center of mass along AP direction, FNS – firm surface + no sound, FS – firm surface + sound, SNS – soft surface + no sound, SS – soft surface + sound.

[a] independent *t*-test between groups of FNS condition, [b] independent *t*-test between groups of FS condition, [c] independent *t*-test between groups of SNS condition, [d] independent *t*-test between groups of SS condition, the significant level was set at $p < 0.05$.

Table 4. Postural control variables of the elderly with ($n = 26$) and without ($n = 26$) knee-OA along the medio-lateral (ML) direction

Parameters	Elderly with knee OA mean ± SD				Elderly without knee OA mean ± SD				*p*-value			
	FNS	FS	SNS	SS	FNS	FS	SNS	SS				
SDCOP$_{ML}$	5.66 ± 1.75	5.07 ± 1.68	12.27 ± 2.88	11.27 ± 3.15	6.80 ± 1.92	5.41 ± 1.28	12.27 ± 3.02	11.24 ± 2.54	0.030[a]	0.417[b]	0.994[c]	0.967[d]
	$F_{(2.004, 50.109)} = 83.287$, $p < 0.001$, $\eta^2 = 0.769$				**$F_{(1.946, 48.655)} = 79.342$, $p < 0.001$, $\eta^2 = 0.760$**							
VCOP$_{ML}$	14.72 ± 5.02	13.88 ± 5.28	37.06 ± 12.54	33.56 ± 10.83	17.88 ± 5.17	15.30 ± 4.85	39.80 ± 18.93	36.61 ± 12.62	0.030[a]	0.316[b]	0.542[c]	0.354[d]
	$F_{(2.172, 54.301)} = 103.557$, $p < 0.001$, $\eta^2 = 0.806$				**$F_{(1.562, 39.039)} = 42.452$, $p < 0.001$, $\eta^2 = 0.629$**							
SDTBCM$_{ML}$	4.48 ± 1.56	3.94 ± 1.42	8.70 ± 2.32	7.68 ± 2.08	5.36 ± 2.04	4.16 ± 1.19	8.41 ± 2.34	7.65 ± 2.21	0.088[a]	0.550[b]	0.656[c]	0.957[d]
	$F_{(2.279, 56.966)} = 54.702$, $p < 0.001$, $\eta^2 = 0.686$				**$F_{(3, 75)} = 41.171$, $p < 0.001$, $\eta^2 = 0.622$**							
VTBCM$_{ML}$	4.96 ± 1.45	4.65 ± 1.60	12.46 ± 3.47	11.40 ± 3.92	5.71 ± 1.63	4.75 ± 1.44	12.03 ± 3.36	11.00 ± 2.84	0.086[a]	0.808[b]	0.656[c]	0.676[d]
	$F_{(1.838, 45.941)} = 86.940$, $p < 0.001$, $\eta^2 = 0.777$				**$F_{(1.881, 47.019)} = 94.312$, $p < 0.001$, $\eta^2 = 0.790$**							
SDCOH$_{ML}$	6.80 ± 2.30	6.13 ± 2.18	13.53 ± 4.10	12.43 ± 4.65	8.31 ± 3.05	6.47 ± 1.87	13.18 ± 4.54	11.91 ± 3.78	0.050[a]	0.555[b]	0.773[c]	0.663[d]
	$F_{(2.084, 52.109)} = 39.794$, $p < 0.001$, $\eta^2 = 0.614$				**$F_{(2.221, 55.535)} = 35.552$, $p < 0.001$, $\eta^2 = 0.587$**							
VCOH$_{ML}$	8.53 ± 2.23	7.23 ± 2.11	18.09 ± 5.61	16.51 ± 4.31	7.61 ± 2.18	7.17 ± 2.35	19.38 ± 6.50	18.53 ± 9.45	0.136[a]	0.923[b]	0.449[c]	0.330[d]
	$F_{(1.639, 40.983)} = 43.477$, $p < 0.001$, $\eta^2 = 0.635$				**$F_{(1.765, 44.121)} = 82.484$, $p < 0.001$, $\eta^2 = 0.767$**							

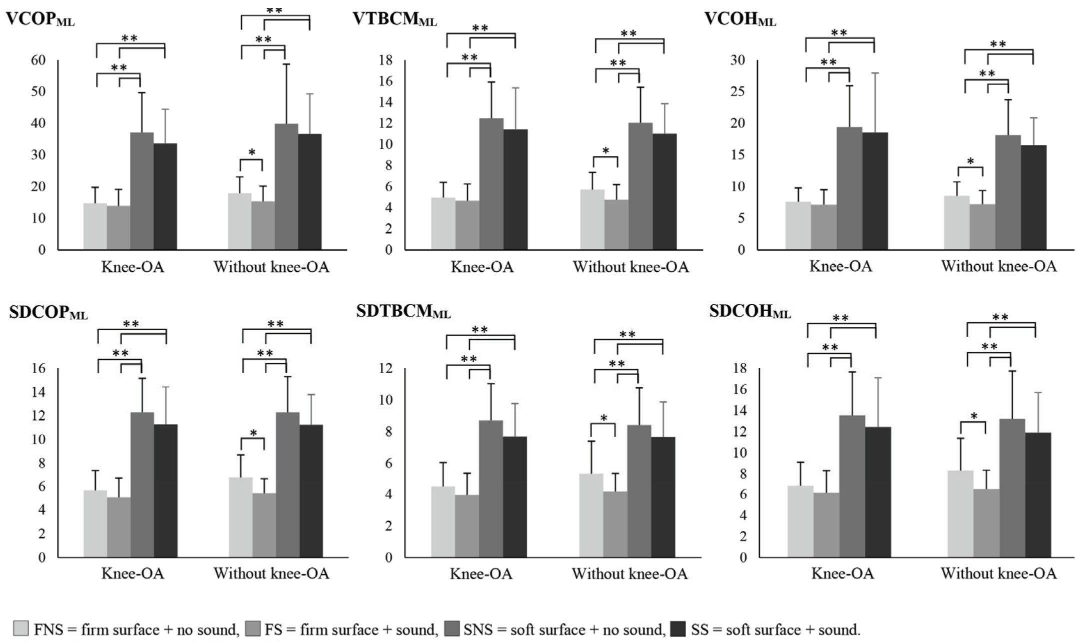
VCOP$_{ML}$ – velocity of center of pressure along ML direction, SDCOP$_{ML}$ – standard deviation of center of pressure along ML direction, VTBCM$_{ML}$ – velocity of total body center of mass along ML direction, SDTBCM$_{ML}$ – standard deviation of total body center of mass along ML direction, FNS – firm surface + no sound, FS – firm surface + sound, SNS – soft surface + no sound, SS – soft surface + sound.

[a] independent *t*-test between groups of FNS condition, [b] independent *t*-test between groups of FS condition, [c] independent *t*-test between groups of SNS condition, [d] independent *t*-test between groups of SS condition, the significant level was set at $p < 0.05$.

Table 5. Pairwise comparisons of the postural control variables of the elderly with and without knee-OA (*p*-value)

Parameters	Elderly with knee OA (n = 26)								Elderly without knee OA (n = 26)							
	Antero-posterior direction				Medio-lateral direction				Antero-posterior direction				Medio-lateral direction			
	FNS	FS	SNS	SS	FNS	FS	SNS	SS	FNS	FS	SNS	SS	FNS	FS	SNS	SS
SDCOP																
FNS	n/a				n/a				n/a				n/a			
FS	1.000	n/a			0.560	n/a			0.506	n/a			**0.006**	n/a		
SNS	**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a	
SS	**<0.001**	**<0.001**	0.407	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	0.140	n/a
VCOP																
FNS	n/a				n/a				n/a				n/a			
FS	1.000	n/a			1.000	n/a			0.707	n/a			**0.046**	n/a		
SNS	**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a	
SS	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	0.746	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	1.000	n/a
SDTBCM																
FNS	n/a				n/a				n/a				n/a			
FS	1.000	n/a			0.738	n/a			1.000	n/a			**0.020**	n/a		
SNS	**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a	
SS	**<0.001**	**<0.001**	0.234	n/a	**<0.001**	**<0.001**	0.581	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	0.423	n/a
VTBCM																
FNS	n/a				n/a				n/a				n/a			
FS	1.000	n/a			1.000	n/a			0.139	n/a			**0.017**	n/a		
SNS	**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a	
SS	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	0.686	n/a	**<0.001**	**<0.001**	0.202	n/a
SDCOH																
FNS	n/a				n/a				n/a				n/a			
FS	1.000	n/a			1.000	n/a			1.000	n/a			**0.021**	n/a		
SNS	**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a	
SS	**<0.001**	**<0.001**	0.283	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	0.401	n/a
VCOH																
FNS	n/a				n/a				n/a				n/a			
FS	1.000	n/a			1.000	n/a			0.531	n/a			**0.029**	n/a		
SNS	**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a		**<0.001**	**<0.001**	n/a	
SS	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	1.000	n/a	**<0.001**	**<0.001**	0.726	n/a	**<0.001**	**<0.001**	0.272	n/a

VCOP – velocity of center of pressure, SDCOP – standard deviation of center of pressure, VTBCM – velocity of total body center of mass, SDTBCM – standard deviation of total body center of mass, FNS – firm surface + no sound, FS – firm surface + sound, SNS – soft surface + no sound, SS – soft surface + sound. The significant level was set at $p < 0.05$.



FNS = firm surface + no sound, FS = firm surface + sound, SNS = soft surface + no sound, SS = soft surface + sound.
The asterisk (*) = p<0.05, double asterisks (**) = p<0.001.
The unit of VCOP, VTBCM, and VCOH is mm/sec, the unit of SDCOP, SDTBCM, and SDCOH is mm.

Fig. 2. The bar charts of postural stability parameters along ML direction for the elderly with and without knee-OA

η^2 = 0.751], $SDTBCM_{ML}$ [$F_{(2.279,\ 56.966)}$ = 54.702, $p < 0.001$, η^2 = 0.686], $SDCOH_{AP}$ [$F_{(3,\ 75)}$ = 62.162, $p < 0.001$, η^2 = 0.713], $SDCOH_{ML}$ [$F_{(2.084,\ 52.109)}$ = 39.794, $p < 0.001$, η^2 = 0.614], $VCOP_{AP}$ [$F_{(2.136,\ 53.405)}$ = 124.110, $p < 0.001$, η^2 = 0.832], $VCOP_{ML}$ [$F_{(2.172,\ 54.301)}$ = 103.557, $p < 0.001$, η^2 = 0.806], $VTBCM_{AP}$ [$F_{(2.181,\ 54.526)}$ = 117.827, $p < 0.001$, η^2 = 0.825], $VTBCM_{ML}$ [$F_{(1.838,\ 45.941)}$ = 86.940, $p < 0.001$, η^2 = 0.777], $VCOH_{AP}$ [$F_{(2.226,\ 55.638)}$ = 95.937, $p < 0.001$, η^2 = 0.793], and $VCOH_{ML}$ [$F_{(1.639,\ 40.983)}$ = 43.477, $p < 0.001$, η^2 = 0.635]. The results of between groups and within groups' comparison for all variables along AP and ML directions are presented in Tables 3 and 4, respectively.

The pairwise comparison for elderly without knee-OA demonstrated significant difference of all variables when compared between SNS and FNS, SNS and FS, SS and FNS, and SS and FS conditions ($p < 0.001$) and between FNS and FS for $SDCOP_{ML}$ ($p = 0.006$), $SDTBCM_{ML}$ ($p = 0.020$), $SDCOH_{ML}$ ($p = 0.021$), $VCOP_{ML}$ ($p = 0.046$), $VTBCM_{ML}$ ($p = 0.017$), and $VCOH_{ML}$ ($p = 0.029$). For the elderly with knee-OA group, the pairwise comparison demonstrated significant differences between FS and SS, FS and SNS, FNS and SS, and FNS and SNS conditions ($p < 0.001$) for all variables. No significant difference was found between FNS and FS, SNS, and SS conditions for all variables. All pairwise comparison results are presented in Table 5. The comparison results of all postural stability parameters along the ML direction for both groups are presented as the bar graphs in Fig. 2.

4. Discussion

Results of this study demonstrated the significant reduction of standard deviation and velocity of postural sway in the presence of sound in the elderly without knee-OA participants. These results partially confirmed our hypothesis that sound could improve postural stability in the elderly, especially in the ML direction. The findings also confirmed the results of previous studies that investigated the effect of sound on standing postural control [9], [4]. Deviterne et al. [4] reported that sound with cognitive load could reduce postural sway during standing in the healthy elderly participants. This reduction of postural sway might associate with the cognitive process for postural control, which is called the dual-task paradigm. This paradigm is that participants are performing two (dual) tasks, which consist of a primary task (postural task) and a secondary task (cognitive task) at the same time. The performance of the primary task is related to the complexity of the secondary task that is called the "invert U-shape model" [13]. If the difficulty of the secondary task is low, the primary task's performance will improve. However, if the secondary task is high complexity, the primary task's performance will decline. For the present study, the reduction of postural sway (improved postural task performance) might be caused by adding the simple counting sound-on task during testing. Another reason for improving postural stability in the elderly without knee OA was that they could use the sound to build up the auditory anchorage [9] and use it as a reference point for controlling static standing posture.

In addition, the 10% reduction of postural sway in the elderly without knee-OA participants was close to the previous results [7], [9], [31]. It was confirmed that sound could reduce postural sway by about 10% in standing task. Moreover, the effect of sound showed more benefit in postural control along the ML direction on the firm surface only. This finding was similar to the study of Gandemer et al. in 2017 [9] which reported no significant effect of sound during standing on the foam surface. In addition, the present study did not find the difference of standing postural control along the AP direction when applied the sound. This may be related to, firstly, the loss of postural control as a result of progressive involution changes due to the ageing process is apparently characterized by the frontal plane instability [9] and, secondly, the static sound sources were placed beside both ears. Thus, the effect of sound was more enhanced in the ML than the AP directions. Lastly, the previous study suggested that auditory system might influence postural control in the ML rather than the AP direction due to the anatomical structure of the auditory system that lies in the lateral side of the head [27]. According to the ability of sound localization is that the human brain can localize the sound source's position by using the differences of the sound intensity and the arrived time between both ears, which calls the "binaural cues" [20]. Moreover, it detects the sound location along the sagittal plane by using the frequency response, which calls the "monaural cues" [2]. The binaural cues, which usually sense to the lateral direction, are more accurate than monaural cues that sense to the midline. Therefore, the sound utilization should assist the body to promote postural control, especially in the ML direction as the above-mentioned.

Both elderly with and without knee-OA groups showed the significant greater postural sway during standing on the soft surface than the firm surface in both AP and ML directions for all variables. The increasing of postural sway during standing on the soft surface was caused by the reduction of somatosensory feedback from feet [22]. In addition, our testing conditions were performed under the eyes closed situation for limitation of the visual feedback information. Thus, the remaining reliable sensory systems were vestibular and auditory systems. In the situations where the remaining information provided by vestibular only (SNS condition) or vestibular and auditory (SS condition), participants could not substitute the loss of visual and reduction of somatosensory feedback to control stable standing posture.

The results of this study demonstrated no significant difference of postural sway variables between both groups in all conditions, except for $SDCOP_{ML}$ and $VCOP_{ML}$ in FNS condition. The elderly with knee-OA group demonstrated smaller postural sway than the elderly without knee-OA group in the FNS condition. In addition, the similar postural control performances of both groups were found in other conditions. The possible explanation may be that the knee-OA group used the stiffness or freezing strategy. Previous study reported that normal elderly participants used the freezing strategy to maintain their standing posture when feedback from visual and somatosensory systems were limited [12]. It might be possible that the elderly with knee-OA group used this strategy to reduce their lower limbs' movement for stabilizing the standing posture. Using this mechanism also helps to avoid pain or discomfort and is called the fear-avoidance model of pain [18]. In the soft surface condition, the elderly with knee-OA group tended to increase their postural sway more than the elderly without knee-OA group. However, this difference did not reach a significant level.

The results demonstrated no significant reduction of postural sway in the sound condition for all variables for the elderly with knee-OA group. This may be associated with different control strategies in the elderly with knee-OA. Some people may choose to stand rigidly to avoid any movement that resulted in pain or sway while standing [18]. Moreover, it might be caused by the simple static sound source used in the study. A recent study of Gandermer et al. [9] compared the effect of sound between the simple and complex sound sources on postural stability. They found that the enriched auditory environment provided more postural stability.

The potential limitation of the study related to the auditory cue was launched from two loudspeakers in lateral direction only. Thus, the effect of sound on postural stability along the front-back direction remains unclear. Another limitation was that the no-sound condition was not complete silence. Participants reported that they still heard a bit of sound when they wore the earmuffs. However, they reported that the earmuffs could obviously reduce environmental sound in the testing room. The suggestion for this issue in the further study was using the earplugs together with the earmuffs to make sure that the no-sound condition will be a complete silence.

In addition, the findings were still unclear about the using of sound to improve postural stability in participants who had proprioceptive problems. So, further study may investigate the effect of sound from multiple sources placed in multiple directions on postural stability in participants with proprioception problems to gain more understanding about the auditory role on postural stability.

The results obtained from this study could be applied to improve postural stability in ageing people. The therapists may use the sound as an add-on option in the balance training program for the elderly. The encouragement of using the sound may bring their attention and using it as the external reference for improving postural control and balance.

5. Conclusions

The effect of sound on the standing postural stability in the elderly without knee-OA was confirmed in this study. The elderly without knee-OA demonstrated more stable stance in the ML direction with the presence of sound. However, the sound did not influence the standing postural stability in the elderly with knee-OA. These findings may encourage the use of the auditory cue for improving balance in the elderly, especially when visual feedback system unavailable.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This research is supported by the "Young Researcher Development Program" provided by the National Research Council of Thailand (NRCT). We thank orthopaedic physical therapists of the Physical Therapy Center, Faculty of Physical Therapy, Mahidol University for their kind support and all the elderly who participated in the study.

References

[1] BANDINELLI S., BENVENUTI E., DEL LUNGO I., BACCINI M., BENVENUTI F., DI IORIO A., FERRUCCI L., *Measuring muscular strength of the lower limbs by hand-held dynamometer: a standard protocol*, Aging (Milano), 1999, 11 (5), 287–293, DOI: 10.1007/BF03339802.

[2] BUTLER R.A., HUMANSKI R.A., *Localization of sound in the vertical plane with and without high-frequency spectral cues*, Percept. Psychophys., 1992, 51 (2), 182–186.

[3] DAVIS R.B., ÕUNPUU S., TYBURSKI D., GAGE J.R., *A gait analysis data collection and reduction technique*, Hum. Mov. Sci., 1991, 10(5), 575–587, DOI: 10.1016/0167-9457(91)90046-z.

[4] DEVITERNE D., GAUCHARD G.C., JAMET M., VANCON G., PERRIN P.P., *Added cognitive load through rotary auditory stimulation can improve the quality of postural control in the elderly*, Brain Res. Bull., 2005, 64 (6), 487–492, DOI: 10.1016/j.brainresbull.2004.10.007.

[5] DOYLE R.J., HSIAO-WECKSLER E.T., RAGAN B.G., ROSENGREN K.S., *Generalizability of center of pressure measures of quiet standing*, Gait Posture, 2007, 25 (2), 166–171, DOI: 10.1016/j.gaitpost.2006.03.004.

[6] DOZZA M., HORAK F.B., CHIARI L., *Auditory biofeedback substitutes for loss of sensory information in maintaining stance*, Exp. Brain Res., 2007, 178(1), 37–48, DOI: 10.1007/s00221-006-0709-y.

[7] EASTON R.D., GREENE A.J., DIZIO P., LACKNER J.R., *Auditory cues for orientation and postural control in sighted and congenitally blind people*, Exp. Brain Res., 1998, 118(4), 541–550, DOI: 10.1007/s002210050310\.

[8] FUJIMOTO C., MUROFUSHI T., CHIHARA Y., USHIO M., YAMAGUCHI T., YAMASOBA T., IWASAKI S., *Effects of unilateral dysfunction of the inferior vestibular nerve system on postural stability*, Clin. Neurophysiol., 2010, 121 (8), 1279–1284, DOI: 10.1016/j.clinph.2010.02.149.

[9] GANDEMER L., PARSEIHIAN G., KRONLAND-MARTINET R., BOURDIN C., *Spatial cues provided by sound improve postural stabilization: Evidence of a spatial auditory map?*, Front Neurosci., 2017, 11, 357, DOI: 10.3389/fnins.2017.00357.

[10] GRACE GAERLAN M., ALPERT P.T., CROSS C., LOUIS M., KOWALSKI S., *Postural balance in young adults: the role of visual, vestibular and somatosensory systems*, J. Am. Acad. Nurse Pract., 2012, 24 (6), 375–381, DOI: 10.1111/j.1745-7599.2012.00699.x.

[11] HAWKER G.A., MIAN S., KENDZERSKA T., FRENCH M., *Measures of adult pain: Visual Analog Scale for Pain (VAS Pain), Numeric Rating Scale for Pain (NRS Pain), McGill Pain Questionnaire (MPQ), Short-Form McGill Pain Questionnaire (SF-MPQ), Chronic Pain Grade Scale (CPGS), Short Form-36 Bodily Pain Scale (SF-36 BPS), and Measure of Intermittent and Constant Osteoarthritis Pain (ICOAP)*, Arthritis Care Res. (Hoboken), 2011, 63 Suppl. 11, S240–252, DOI: 10.1002/acr.20543.

[12] HSU W.L., LIN K.H., YANG R.S., CHENG C.H., *Use of motor abundance in old adults in the regulation of a narrow-based stance*, Eur. J. Appl. Physiol., 2014, 114 (2), 261–271, DOI: 10.1007/s00421-013-2768-7.

[13] HUXHOLD O., LI S.C., SCHMIEDEK F., LINDENBERGER U., *Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention*, Brain Res. Bull., 2006, 69(3), 294–305, DOI: 10.1016/j.brainresbull.2006.01.002.

[14] JACOBSON L.T., *Definitions of osteoarthritis in the knee and hand*, Ann. Rheum. Dis., 1996, 55(9), 656–658.

[15] KARIM A.M., RUMALLA K., KING L.A., HULLAR T.E., *The effect of spatial auditory landmarks on ambulation*, Gait Posture, 2018, 60, 171–174, DOI: 10.1016/j.gaitpost.2017.12.003.

[16] KHALAJ N., ABU OSMAN N.A., MOKHTAR A.H., MEHDIKHANI M., WAN ABAS W.A., *Balance and risk of fall in individuals with bilateral mild and moderate knee osteoarthritis*, PLoS One, 2014, 9 (3), e92270, DOI: 10.1371/journal.pone.0092270.

[17] LE CLAIR K., RIACH C., *Postural stability measures: what to measure and for how long*, Clinical Biomechanics, 1996, 11 (3), 176–178, DOI: 10.1016/0268-0033(95)00027-5.

[18] LEEUW M., GOOSSENS M.E., LINTON S.J., CROMBEZ G., BOERSMA K., VLAEYEN J.W., *The fear-avoidance model of musculoskeletal pain: current state of scientific evidence*, J. Behav. Med., 2007, 30 (1), 77–94, DOI: 10.1007/s10865-006-9085-0.

[19] LEQUESNE M.G., MERY C., SAMSON M., GERARD P., *Indexes of severity for osteoarthritis of the hip and knee. Validation – value in comparison with other assessment tests*, Scand. J. Rheumatol. Suppl., 1987, 65, 85–89.

[20] MCLAUGHLIN S.A., HIGGINS N.C., STECKER G.C., *Tuning to binaural cues in human auditory cortex*, J. Assoc. Res. Otolaryngol., 2016, 17 (1), 37–53, DOI: 10.1007/s10162-015-0546-4.

[21] NASREDDINE Z., HEMRUNGROJN S., *Montreal cognitive assessment (MoCA) Thai version*, 2011, https://www.mocatest.org/wp-content/uploads/2015/tests-instructions/MoCA-Test-Thai.pdf. Accessed 14 Mar. 2018.

[22] PATEL M., FRANSSON P.A., LUSH D., GOMEZ S., *The effect of foam surface properties on postural stability assessment while standing*, Gait Posture, 2008, 28 (4), 649–656, DOI: 10.1016/j.gaitpost.2008.04.018.

[23] PETERKA R.J., *Sensorimotor integration in human postural control*, J. Neurophysiol., 2002, 88(3), 1097–1118, DOI: 10.1152/jn.2002.88.3.1097.

[24] PIROZZO S., PAPINCZAK T., GLASZIOU P., *Whispered voice test for screening for hearing impairment in adults and children: systematic review*, BMJ, 2003, 327 (7421), 967, DOI: 10.1136/bmj.327.7421.967.

[25] PUSZCZALOWSKA-LIZIS E., BUJAS P., OMORCZYK J., *Postural stability in women in the eighth and ninth decades of life*, Acta Bioeng. Biomech., 2016, 18 (3), 115–121.

[26] RAY C.T., HORVAT M., CROCE R., MASON R.C., WOLF S.L., *The impact of vision loss on postural stability and balance strategies in individuals with profound vision loss*, Gait Posture, 2008, 28 (1), 58–61, DOI: 10.1016/j.gaitpost.2007.09.010.

[27] SAKELLARI V., SOAMES R.W., *Auditory and visual interactions in postural stabilization*, Ergonomics, 1996, 39 (4), 634–648, DOI: 10.1080/00140139608964486.

[28] SPEERS R.A., KUO A.D., HORAK F.B., *Contributions of altered sensation and feedback responses to changes in coordination of postural control due to aging*, Gait Posture, 2002, 16 (1), 20–30.

[29] TANAKA T., KOJIMA S., TAKEDA H., INO S., IFUKUBE T., *The influence of moving auditory stimuli on standing balance in healthy young adults and the elderly*, Ergonomics, 2001, 44 (15), 1403–1412, DOI: 10.1080/00140130110110601.

[30] YAMAMOTO R., KINOSHITA T., MOMOKI T., ARAI T., OKAMURA A., HIRAO K., SEKIHARA H., *Postural sway and diabetic peripheral neuropathy*, Diabetes Res. Clin. Pract., 2001, 52 (3), 213–221, DOI: 10.1016/S0168-8227(01)00236-4.

[31] ZHONG X., YOST W.A., *Relationship between postural stability and spatial hearing*, J. Am. Acad. Audiol., 2013, 24(9), 782–788, DOI: 10.3766/jaaa.24.9.3.