Body balance function of cochlear implant patients with and without sound conditions

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Highlights

The center of pressure of cochlear implant patients was measured in an anechoic room.

The center of pressure shifted laterally in silent condition with their eyes closed.

This abnormal shift was eliminated with sound.

Abstract

Objective: The relation between well-controlled auditory stimulation through cochlear implant (CI) and the body balance has been sparsely investigated. The purpose of this study was to evaluate the body balance function of CI patients with- and without-sound in anechoic sound-shielded room.

Methods: We recorded 8 experienced CI recipients and 8 young normal-hearing volunteers. All subjects were assessed using posturography under 4 conditions: (1) eyes open with-sound, (2) eyes closed with-sound, (3) eyes open without-sound, and (4) eyes closed without-sound.

Results: The total path length and the total area were significantly larger in the eyes closed condition than in the eyes open condition. In normal hearing subjects, the average displacement of center of pressure (COP) in the mediolateral direction under with-sound condition was not different from that under without-sound condition. In CI recipients, the COP significantly displaced to the CI side after the deprivation of visual cues in without-sound condition. This shift was eliminated in with-sound condition (significant interaction among sound condition, eye condition, and between-group factor).

Conclusion: In CI subjects, sound stimulation improves the abnormal displacement of COP in the mediolateral direction.

Significance: A posturographic study under an anechoic condition proved that sound stimulation improves body balance function in CI subjects.

Keywords: cochlear implant, posturography, anechoic

Abbreviations

CI: cochlear implant, COP: center of pressure

1. Introduction

A cochlear implant (CI) is a standard treatment for profound sensorineural hearing loss patients where hearing aids are no longer sufficient. A CI is generally comprised of a speech processor, a receiver-stimulator, and an electrode array. The receiver-stimulator is surgically implanted subcutaneously behind the ear, while the electrode array is inserted into the cochlea. The sound is sensed and processed in the speech processor. The processed sound signal is transcutaneously transmitted to the receiver-stimulator which stimulates the intracochlear electrode according to the transmitted sound signal. A CI facilitates good speech understandings in both postlinguistically and prelinguistically deafened patients (Waltzman et al., 1994, Hiraumi et al., 2007).

CI surgery is known to affect vestibular function, an important role of the inner ear (Rah et al., 2016). A recent meta-analysis study showed that CI surgery has a significant negative effect on the function of the lateral semicircular canal and the saccule (Ibrahim et al., 2017). While most of the studies which have evaluated the effect of CI on the vestibular function focus on the surgical invasiveness of the procedure (Rah et al., 2016), little is known about effects of sound application through CI on balance function.

Although the effects of auditory input on the balance function in CI recipients have been explored using posturography, the results are inconsistent. In a study which evaluated 50 cochlear implant patients with the device switched off and on, significantly poorer equilibrium scores were obtained under static condition when the CI was switched on (Schwab et al., 2010). In another study which compared the sway velocity and circular area in 24 CI recipients, it was noted that these two parameters (sway velocity and circular area) did not change after turning off the CI (Huang et al., 2011). In a similar study by Mazaheryazdi et al. (2017) involving 25 CI recipients, a significant improvement was noted in the anterior-posterior displacement, the mediolateral displacement, the area, and the velocity in open eyes conditions, when the CI was turned on . One of the reasons for this discrepancy is the uncontrolled sound stimulation in all these studies which adopted natural environmental sound during the measurement.

Two mechanisms are speculated to explain the effect of CI activation on body balance.

Improved spatial sensation provided by the auditory cues is the first mechanism. Although the auditory space perception is not usually involved in the regulation of body balance in normal subjects, it may be recruited in postural control in a patient with bilateral inner ear disorder (Rumalla et al., 2015). The other suggested mechanism is the electrical activation of otolith organs. A recent study noted that electrical stimulation through CI activates the otolith organs (Parkes et al., 2017). The activated saccule may improve the body balance in the static condition. However, the unsteadiness of sound can be problematic in both hypotheses; the echoic sound and multiple sound sources may disrupt the auditory space recognition, and the fluctuation of sound intensity may result in the intermittent vestibular stimulation. Therefore, precise sound control is needed to evaluate the actual influence of CI activation on body balance.

In this study, we investigated the body balance function of CI patients in an anechoic, sound shielded room using posturography to clarify the effect of CI activation

2. Methods

2.1 Subjects

We evaluated 8 hearing-loss patients with CI on one side. They were recruited at Iwate Medical University (4 males, 4 females; aged between 20 and 61 years, mean 44.0 years). All the subjects had been using CI for more than 3 years (3-21 years, mean 10.4 years). The hearing threshold with CI is 23-33 dBHL (mean 29.4 dBHL). Eight young normal-hearing paid volunteers (3 males, 5 females; aged between 20 and 24 years, mean 21.5 years) with no history of neurological or muscular diseases and who showed normal hearing threshold were recruited as controls..

All of the subjects gave written informed consent, and the study protocol was approved by the Ethics Committee of Iwate Medical University (H28-78) and Iwate Prefectural University (183), in accordance with the Declaration of Helsinki.

2.2 Postural sway measurement

All subjects were assessed using posturography (GP-5000, Anima Co., Ltd., Tokyo, Japan) in an anechoic room. All subjects were required to stand on a flat platform with the feet close together for 60 s. The medial surface of the toes and the calcanei were aligned to the center line of the platform. The CI recipients wore their CI during the experiment. The force transducers embedded in the platform continuously measured the displacement of the center of foot pressure (COP) with a sampling frequency of 20

Hz. COP is about the same as the position of the center of gravity while standing still. The total path length, the total path area, and the average displacement of COP in the anteroposterior and mediolateral directions were calculated. The displacement of COP was measured from a reference point which was set at the midpoint of the tip of the toes and the calcanei along the center line.

The posturographic measurement were conducted under 4 conditions; (1) eyes open with sound stimuli, (2) eyes closed with sound stimuli, (3) eyes open without sound stimuli, and (4) eyes closed without sound stimuli. The sequence of the four conditions was counterbalanced among subjects. In conditions with sound stimuli, white noise (70 dBA at the position of the head center of each subject) were delivered from a loud speaker (101VM, BOSE, Massachusetts, USA, frequency range 70 – 17,000 Hz :IEC60581-7) placed 1 m anterior to the subjects at their ear level. The position of the speaker was adjusted with a laser level (AL-50V, OHTA manufactory, Tokyo, Japan) and a laser rangefinder (LS-411, MAX Co., Ltd., Tokyo, Japan). All the measurements were conducted in an anechoic room constructed by Wakabayashi Acoustic Design Corporation (Tokyo, Japan). The size of the room was 5,400 mm (width) x 4,800 mm (length) x 3,000 mm (height). The ambient noise level is less than 15 dBA between 125 - 16,000 Hz. At the center of this room, the free-field decay of sound from a point source was verified to follow the inverse square law between 250 – 8,000 Hz. These were measured using a microphone, a preamplifier, and a measuring amplifier, calibrated with an acoustic calibrator (Type 4190, Type 2669, Type 2636, and Type 4226, respectively, Bruel&Kjaer, Naerum, Denmark).

2.3 Statistical analysis

The total path length, the total path area, and the average displacement of the COP were examined by two-way repeated measures and mixed factorial analyses of variance (ANOVA) with a within-group factor of eye conditions (eyes open / eyes closed), and sound conditions (with-sound / without-sound) and a between-group factor (CI recipients / normal hearing subjects). The average displacement of COP was analyzed separately in the 2 directions; anteroposterior and mediolateral axes. In the anteroposterior axis, the anterior displacement was defined as positive. In the mediolateral axis, the CI side was defined as positive in the CI recipients. In the control group, right side was defined as positive. Post-hoc pairwise comparison with Bonferroni adjustment was conducted when the interaction among the conditions were significant. *P* values <.05 were considered significant. All analyses were conducted using SPSS software (IBM SPSS Statistics 24 for Windows, Advanced Analytics Inc., Tokyo)

3. Results

The demographic data of the subjects are summarized in Table 1. No history of neurological or muscular diseases other than the hearing loss was reported. No subjects required assistance to prevent falling during the experiment in the 4 conditions described above. No adverse effects were observed before, during, and after the experiment. All the parameters (the total path length, the total path area, and the average displacement of the COP in the anteroposterior and mediolateral axes) were obtained in all the subjects. The overall results are summarized in Table 2.

3.1 Analysis of the total length

The ANOVA revealed significant influence of the eye condition. The total path length was significantly longer in the eyes closed condition than in the eyes open conditions (F (1, 14) = 45.94, P = 0.00). The sound application did not affect the total path length (F (1, 14) = 0.88, P = 0.37). The difference between the CI recipients and the normal hearing subjects was not significant (F (1, 14) = 0.11, P = 0.74). No interaction was statistically significant.

3.2 Analysis of the total area

The area was significantly larger in the eyes closed condition than in the eyes open conditions. The difference was statistically significant (F (1, 14) = 17.89, P = 0.00). The main effect of sound application was not significant (F (1, 14) = 2.49, P = 0.14). The difference between the CI recipients and the normal hearing subjects was not significant (F (1, 14) = 0.03, P = 0.86). No significant interaction was observed.

3.3 Analysis of the average displacement of COP in the anteroposterior axis

The averaged COP was positioned significantly anterior in the eyes closed condition than in the eyes open conditions (F (1, 14) = 9.63, P = 0.01). The sound condition did not affect the average displacement of COP in the anteroposterior direction (F (1, 14) = 0.95, P = 0.35). The difference between the CI recipients and the normal hearing subjects was not significant (F (1, 14) = 1.05, P = 0.32). The anteroposterior displacements of COP in individual subjects are shown in Figure 1.

3.4 Analysis of the average displacement of COP in the mediolateral axis

The ANOVA showed that the interaction among sound condition, eye condition, and between-group factor was significant ($F (1, 14) = 5.09$, $P = 0.04$). The mediolateral displacements of COP in individual subjects are shown in Figure 2. Post-hoc pairwise comparison with Bonferroni adjustment was conducted to further analyze the interaction. In the normal hearing subjects, the average displacement of COP with eyes open condition was not different from that with eyes closed condition in both with-sound and without-sound conditions ($P= 0.46$, $P= 0.28$, respectively). In the CI recipients under without-sound condition, the average displacement of COP with eyes closed condition significantly shifted to the CI side compared to that with eyes open condition ($P = 0.02$, pairwise comparison with Bonferroni adjustment). In with-sound condition, this shift disappeared and the average displacement of COP in the mediolateral axis was not different from the eyes open and eyes closed conditions ($P = 0.53$).

The ANOVA also showed that the COP in CI recipients was deviated to the non-CI side ($F (1, 14) = 5.55$, $P = 0.03$). The full results of the ANOVA are shown in Table 3.

4. Discussion

In this study, we showed that the average mediolateral displacement of COP deviated to the CI side in silent and anechoic condition after the deprivation of the visual cues. This COP shift disappeared in the with-sound condition. With visual cues, the COP in the CI recipients was positioned to the non-CI side in comparison with the normal subjects, which may be resulting from the compensatory effect to the reduced vestibulospinal reflex in the CI side. In silent condition without visual cues, this compensatory effect seems to be reduced. The auditory stimulation returned the COP to the position before the deprivation of the visual cues. The ANOVA showed significant interaction among 3 factors (sound condition, eye condition, and between-group factor), and the post-hoc test proved the above mentioned conclusion. In the pilot study in a non-anechoic room, we found that the effect of sound changed according to the position of the speaker and the subjects. The frequency pattern of sound also affected the results. This pilot study motivated us to use an anechoic room. In the anechoic room, the results were very stable, as was shown in this paper. Recent meta-analysis showed that CI surgery can significantly affect the vestibular function (Ibrahim et al., 2017). Despite the high prevalence of the vestibular damage after CI surgery, only a few patients experience long-lasting dizziness (Ibrahim et al., 2017). None of the patients in our study complained about the dizziness at the time of the experiment. This is usually attributed to the compensatory effects. Parietti-Winkler et al. reported in their posturographic study that the compensation occurred within 1 year after CI surgery (Parietti-Winkler et al., 2015).

In our study, total length and the total area of sway with eyes open were not different between CI recipients and the normal subjects, which is in accordance with previous reports (Huang et al., 2011, Parietti-Winkler et al., 2015). This result suggests that the asymmetric vestibular function was well compensated in the static condition. In addition to this compensatory function, our present results suggested that the activation of CI has beneficial effect on the body balance function. COP shift after eye closure is a potential balance disturbance. The sound stimulation through CI eliminated the COP shift, which may improve the body balance in the condition with unstable visual cues.

The elimination of the COP shift can be attributed to the electrical stimulation of the vestibule. Recent studies have reported that the current of the intracochlear electrodes spread to the otolith organs (Parkes et al., 2017). Since the stimulation of the vestibule causes displacement of COP in the mediolateral direction (Yang et al., 2015), current spread to the vestibule generally displaces the COP to the opposite side of CI.

Gnanasegaram et al. (2016) conducted static subjective visual vertical test in CI patients to assess the otolith organ function. Abnormal visual tilts were found in nearly half of the CI recipients. Electric CI stimulation shifted this abnormal tilt towards center. This benefit was most prominent when the stimulation was provided from the side of the impaired ear. Interestingly, some benefit was realized when the opposite ear was stimulated (Gnanasegaram et al., 2016). This result suggests that the electric CI stimulation corrects the abnormal perception of body position, as well as it displaces the COP in the mediolateral direction.

In the anteroposterior direction, the average displacement of COP was not affected by the sound stimulation. The electrical stimulation of the vestibule may change the COP in this direction, but such effect was not observed. In the anteroposterior axis, the COP in CI recipients is not different from that of normal subjects. We speculate that the CI can modulate the abnormal balance but its effect is not so strong as to change the normal balance.

Schwab et al. (2010) speculated that the auditory space perception contributed to the body balance function in CI recipients; but the effect was not observed in the present study. The total length and the total area, which are supposed to improve with auditory space perception, were not influenced by the use of an auditory cue through their CI. Auditory space perception is reported to contribute to body balance in patients with inner ear disturbance. Rumalla et al., measured postural stability in bilateral hearing-aid users aged over 65 years (Rumalla et al., 2015). They reported that static body balance was significantly better in the aided than the unaided condition.

Vitkovic et al. (2016) measured total path lengths in normal balance subjects and vestibular dysfunction subjects. The vestibular impaired subjects had higher path lengths compared to the subjects with normal balance, and the difference increased in the absence of sound. These findings suggest that the vestibular dysfunction subjects utilize their auditory cues, whereas those with normal vestibular function do not. These studies hypothesize that the mechanism of the improvement is due to auditory space recognition. The sound localization ability contributes for the improvement in body sway in the horizontal plane. In our study, we used a point sound source in an anechoic sound shielded room to maximize the sound localization ability; nevertheless, the total path length and the total area did not improve with sound application in CI subjects. This result corresponds to the study of Huang et al. (2011). Huang et al. (2011) compared static balance function in children with their implant on and off. The sway velocity and total area were similar whether or not the CI was activated. It seems natural that CI subjects do not utilize the auditory cues in the body stabilization because the sound localization ability is low in CI subjects. Grantham et al. reported that the range of azimuth error was from 22.0° to 59.3°, which was much larger than that of normal subjects (5.6°) (Grantham et al. , 2008). This poor sound localization ability does not seem to contribute to the body stabilization. Regarding these, the effect of auditory stimulation for body balance improvement in CI recipients is not due to the acoustic space perception but to direct vestibular stimulation.

We conducted this study in an anechoic room to eliminate the effect of the reverberant sound. The reverberant sounds are known to affect the spatial cue of sound, and the effect of the sound in the non-anechoic environment can be different from the present results. An animal study using inferior colliculus neurons of rabbits showed that the reverberant sound sharpen the azimuth tuning in the monaural hearing condition (Kuwada et al., 2014). Although our present study did not show the effect of spatial cue, this can potentially affect the body balance in a challenging condition. The sharpened tuning in CI recipients does not necessarily improve the body balance. The microphone of a CI is omnidirectional, and the sharpened azimuth tuning may emphasize a discrepancy between the auditory cue and the actual body position. To clarify this, further study using anechoic and non-anechoic condition is needed.

There are a few limitations of this study. Firstly, the study enrolled a comparatively small number of subjects. A limited number of subjects were enrolled as the safety of the anechoic room for the CI recipients is not clearly established. Secondly, the average age of the CI recipients and the normal hearing subjects were considerably different. We selected young healthy subjects as controls because we wanted to use absolutely normal subjects. Postlinguistically deafened CI recipients with young age were very rare and we were not able to match the age. The posturography with flat platform does not discriminate between young and older adults (van Wegen et al., 2002), and we think the age difference can be accepted. Thirdly, only a firm flat platform without foam was used. In the clinical test of sensory interaction on balance, a foam platform is used in addition to the firm platform (Kluenter et al., 2009). The foam posturography is reported to be useful for assessing equilibrium in patients with peripheral vestibulopathy (Fujimoto et al., 2009). However, the foam platform was not used as some subjects were not able to complete the tests with it in the pilot study. Nevertheless, we found the beneficial effect of auditory stimulation thorough CI to the body stabilization in static condition. The effect of CI in the dynamic and challenging condition is to be explored.

5. Conclusion

In CI subjects, sound stimulation improves the abnormal displacement of COP in the mediolateral direction after the deprivation of visual cue, which was supported by a significant interaction among sound condition, eye condition, and between-group factor. This may contribute to maintenance of body balance in case of unsteady visual information. Further studies are needed to prove the effect of auditory information thorough CI in real life situations.

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Figure Legend

Figure 1

The displacement of the center of pressure in the anteroposterior direction in each subject.

Positive value means the displacement to the anterior side. CI means cochlear implant, and COP means the center of pressure. In both cochlear implant recipients and normal hearing subjects, the center of pressure displaced anteriorly when their eyes were closed. No statistically significant difference were observed between the cochlear implant recipients and normal hearing subjects,

Figure 2

The displacement of the center of pressure in the mediolateral direction in each subject.

Positive value means the displacement to the cochlear implant side (cochlear implant recipients) or to the right (normal hearing subjects). CI means cochlear implant, and COP means the center of pressure. In cochlear implant recipients, the center of pressure displaced to the cochlear implant side in without-sound condition (Fig 2-b). This abnormal shift is eliminated in with-sound condition (Fig 2-a). In normal hearing subjects, the displacement of the center of pressure was not affected by the eye condition (Fig 2-c and -d).

Table 1
The background of the cochlear implant recipients

No	Age	Sex	Etiology of hearing loss	CI side	Duration of CI use	Type of CI
1	45	M	idiopathic	L	6 years	MEDEL PULSARci100 standard
2	36	F	idiopathic	L	3 years	MEDEL CONCERTO FLEX24
3	38	F	idiopathic	R	10 years	Cochlear CI24R
4	61	M	idiopathic	R	3 years	Cochlear CI422
5	46	F	idiopathic	R	13 years	Cochlear CI24M
6	45	F	idiopathic	R	21 years	Cochlear N22
7	20	M	meningitis	R	17 years	Cochlear CI24M
8	60	M	idiopathic	L	15 years	Cochlear CI24M

CI: cochlear implant

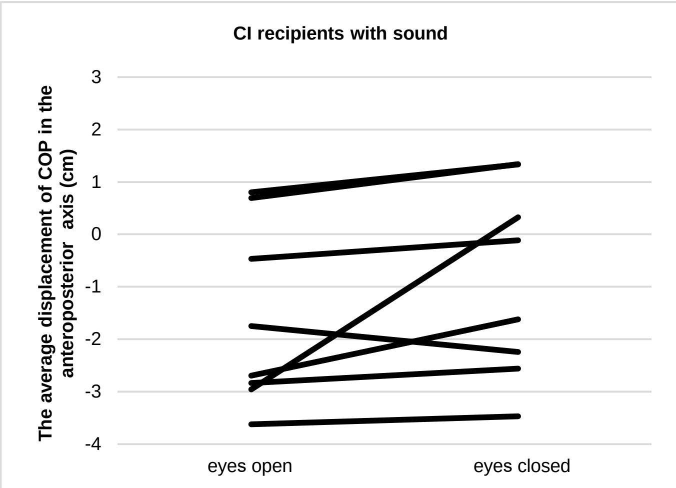
Table 2
Results of static posturography in CI recipients and NH subjects

		CI recipients	NH subjects
		Mean (SEM)	Mean (SEM)
Total Length (cm)			
Sound (+)	EO	54.39(5.70)	49.69(3.60)
	EC	94.12(17.98)	91.26(9.68)
Sound (-)	EO	53.55(5.78)	52.93(5.70)
	EC	104.56(17.81)	95.50(10.18)
Total Area (cm2)			
Sound (+)	EO	2.12(0.37)	1.57(0.26)
	EC	3.64(1.20)	4.13(1.07)
Sound (-)	EO	2.13(0.38)	2.29(0.66)
	EC	4.24(1.09)	4.86(1.10)
Mean displacement of COP (anteroposterior) (cm)			
Sound (+)	EO	-1.60(0.61)	-2.99(0.35)
	EC	-0.88(0.65)	-1.37(0.33)
Sound (-)	EO	-1.37(0.39)	-2.05(0.38)
	EC	-0.60(0.66)	-1.62(0.41)
Mean displacement of COP (mediolateral) (cm)			
Sound (+)	EO	-0.31(0.16)	0.10(0.87)
	EC	-0.27(0.21)	0.16(0.09)
Sound (-)	EO	-0.24(0.13)	0.27(0.10)
	EC	-0.03 (0.13)	0.18(0.06)

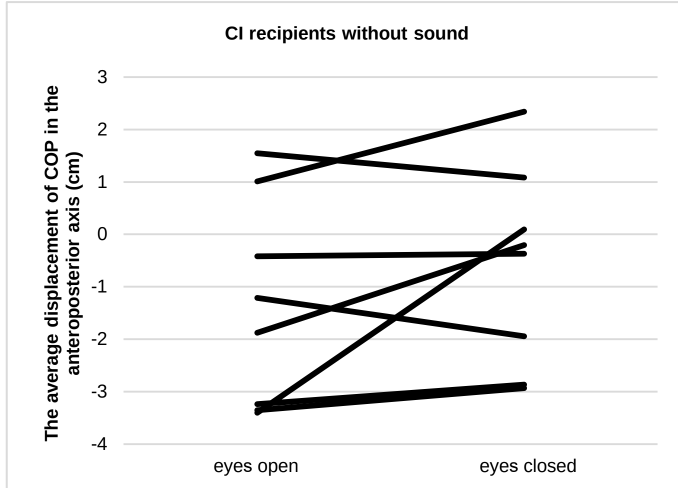
CI: cochlear implant, NH: normal hearing, COP: center of pressure, SEM: standard errors of the mean, EO: eyes open, EC: eyes closed

Table 3
Results of the analysis of variance for the average displacement of COP in the mediolateral axis

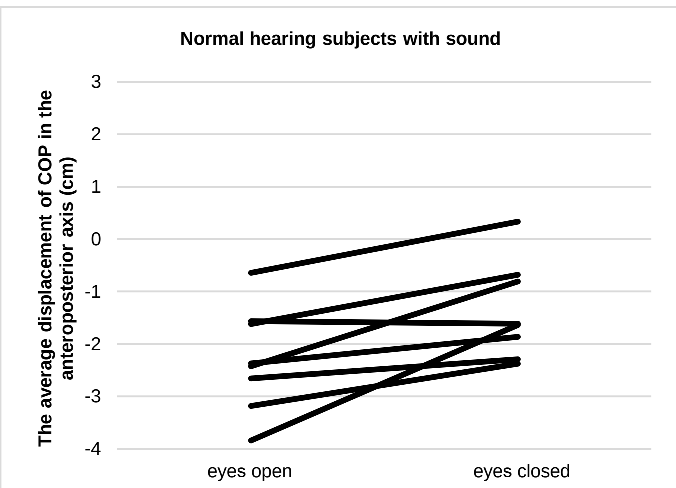
	Factor	F value	P Value
Main effects	Eye conditions	F (1, 14) = 1.76	p = 0.21
	Sound conditions	F (1, 14) = 4.07	p = 0.06
	Group	F (1, 14) = 5.55	p = 0.03
Interaction	Eye conditions * group	F (1, 14) = 3.04	p = 0.10
	Sound conditions * group	F (1, 14) = 0.24	p = 0.63
	Eye conditions * sound conditions	F (1, 14) = 0.02	p = 0.90
	Eye conditions * sound conditions * group	F (1, 14) = 5.09	p = 0.04


CI recipients with sound
The average displacement of COP in the anteroposterior axis (cm)
3
2
1
0
-1
-2
-3
-4
eyes open
eyes closed

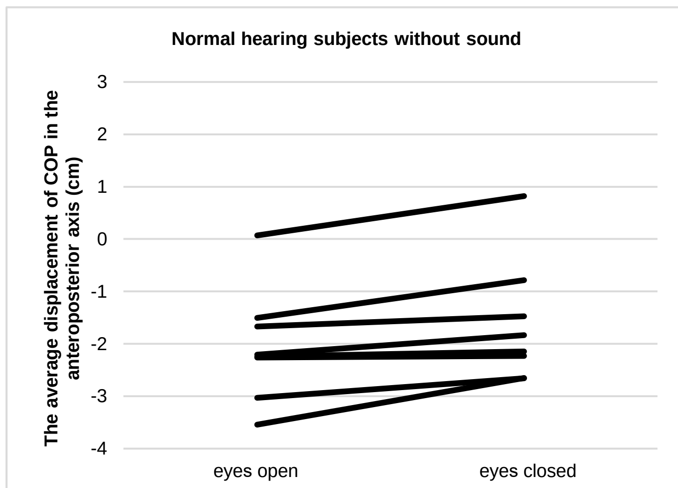
(a)


CI recipients without sound
The average displacement of COP in the anteroposterior axis (cm)
3
2
1
0
-1
-2
-3
-4
eyes open
eyes closed

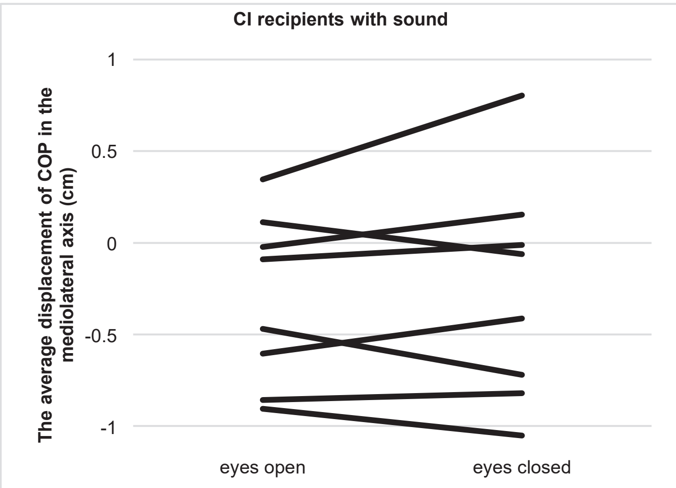
(b)


Normal hearing subjects with sound
The average displacement of COP in the anteroposterior axis (cm)
3
2
1
0
-1
-2
-3
-4
eyes open
eyes closed

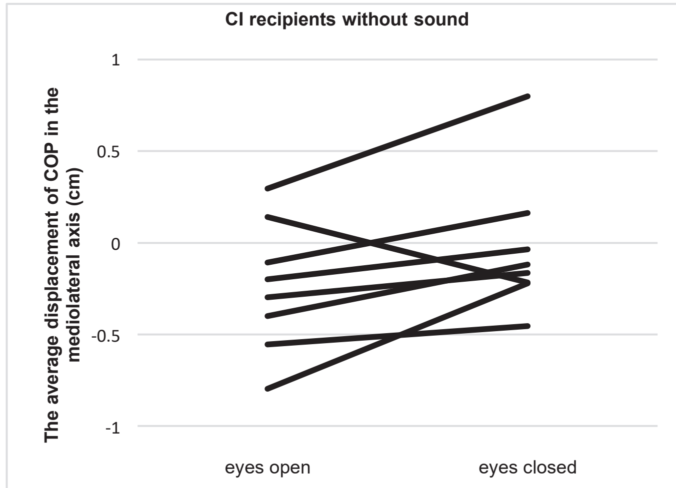
(c)


Normal hearing subjects without sound
The average displacement of COP in the anteroposterior axis (cm)
3
2
1
0
-1
-2
-3
-4
eyes open
eyes closed

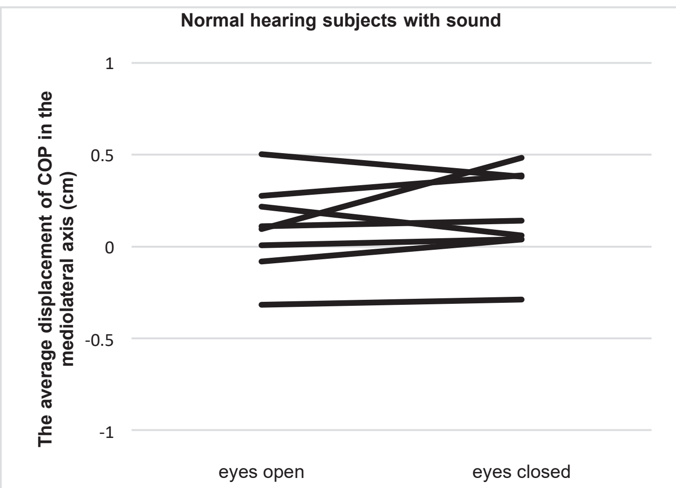
(d)


CI recipients with sound
The average displacement of COP in the mediolateral axis (cm)
1
0.5
0
-0.5
-1
eyes open
eyes closed

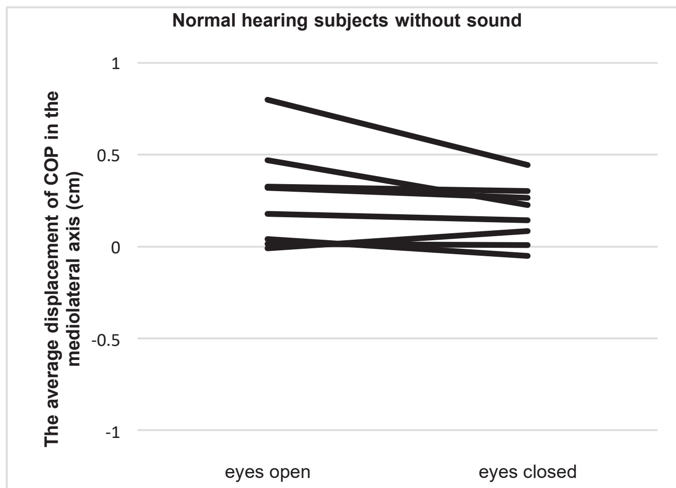
(a)


CI recipients without sound
The average displacement of COP in the mediolateral axis (cm)
1
0.5
0
-0.5
-1
eyes open
eyes closed

(b)


Normal hearing subjects with sound
The average displacement of COP in the mediolateral axis (cm)
1
0.5
0
-0.5
-1
eyes open
eyes closed

(c)


Normal hearing subjects without sound
The average displacement of COP in the mediolateral axis (cm)
1
0.5
0
-0.5
-1
eyes open
eyes closed

(d)