D. 考察

Ⅰ. 歩行運動における頭部の安定化について

歩行をはじめとする日常動作において体平衡が自動的に維持されるためには、脳内において空間識に基づいた運動制御が行われる必要があるとされる。空間識とは、自己と周囲空間の相対的位置関係の認知であり、複数の感覚入力を統合して脳内に周囲の３次元空間を再現することにより達せられる[18),19)]。

今回の実験では、２０代５０代ともに歩行時頭部運動のうち、頭部上下動、pitch、roll 運動が開眼時に比べて遮眼時に有意に減少した。つまり、遮眼歩行時には垂直方向の成分を含む頭部運動が減少するという結果が得られた。

視覚入力が遮断された場合、脳内に再現される３次元空間が不完全なものになり歩行制御に支障を来す。空間識の精度を少しでも高め安定した歩行運動を継続するために、視覚以外の感覚入力の感度(sensitivity)を高める必要が生じる。

ひとつには、運動方向の加速度検出する耳石器（卵形嚢斑）の感度を高めるために、頭部の上下動揺を抑え、かつ頭部の鉛直性（verticality）を保つような歩行様式が選択されたのではないかと考えられる。すなわち、まず頭部の安定化を図ることにより体幹部の歩行運動を安定させるというメカニズムである（top-down 制御）[2),4)]。もうひとつは、下肢深部知覚の感度を高めるために、足底の離床時間を短く接地時間を長くするような歩行様式が選択され、その結果として頭部運動が減少した可能性も考えられる。つまり、歩行中体幹部の安定を優先させ、その結果頭部も安定化するというメカニズムである（bottom-up 制御）[2)]。

耳石器入力依存も下肢深部知覚入力依存も、中枢での空間識の成立に重要な役割を担っており、両者は中枢において複雑に絡み合って働いていると考えられる[2),15),16)]。遮眼歩行時にどちらの入力がより優位であるか決定するのは難しいが、今回の実験では、遮眼歩行時に頭部 yaw 運動には変化がみられなかった。つまり、遮眼時には頭部の上下動揺を抑え、鉛直性を保つことが歩行継続にとってより重要であると推察される。このことは top-down 制御の考えを支持する結果のひとつであると思われる。

Ⅱ. 歩行時頭部運動に対する加齢の影響について

これまでの歩行解析に関する多くの報告において、頭部は上下動に伴ってその位置が高い時に前屈し低い時に後屈する pitch 運動を行い[4)~7), 9)~11)]、一側の下肢接地時には体幹は同方向に、頭部はその反対方向に roll 運動を行う[8)~10)]といった協調運動が観察されている。こうした歩行中の頭部の回転運動は、歩行中の重心の動揺を補償し、体平衡の安定を維持するという生理的な意義を持つとされる[2),4),5),7),9),10)]。

以前我々が若年層を中心に行った歩行解析においても、同様の協調運動が観察された[13)]。また今回の実験においても、上下動に伴ってその位置が高い時に前屈し低い時に後屈するという頭部 pitch 運動は20代50代ともに確認された。しかし、頭部、体幹 roll 運動に関しては２０代と５０代の被験者の間にかなりの相違がみられた。すな

わち、ほとんどの２０代被験者ではこれまでの報告と同様に歩行中頭部と体幹が逆方向に roll 運動を行っている所見（負の相関）がみられたが、５０代被験者では、頭部と体幹が同方向に roll 運動する所見（正の相関）が多くみられた。

頭部、体幹 roll 運動が負の相関を示す被験者の場合、頭部と体幹の左右動は相殺され小さくなり、歩行中空間に対して頭部の安定が保たれている。また、ほとんどの２０代被験者では遮眼歩行においても頭部、体幹協調運動のパターンは変わらず負の相関を示した。このことは、若年者では中枢での空間識形成において前庭入力の関与が大きく、視覚入力依存度が低いことを示していると考えられる。

これに対して頭部、体幹 roll 運動が正の相関を示す被験者の場合、体幹の roll に頭部の roll が加算され頭部の左右動揺がさらに大きくなり、歩行中頭部は空間に対して不安定となる。また、５０代被験者では遮眼時に正の相関を示す被験者がさらに多くなる。このことは、空間識に基づく歩行制御において視覚入力依存度が高いことを示していると考えられる。これらの所見は５０代健康成人の潜在的な前庭機能の低下を表していると思われる。すなわち、今回の３次元動作解析システムを用いた歩行解析により、従来の平衡機能検査や歩行検査では検出し得なかった加齢による歩行様式の変化が客観的に示されたものと考えている。

今後はさらに高齢者で解析を行い、歩行運動に対する加齢の影響を力学的な面や平衡神経学的な面から考察し、ひいては高齢者の転倒問題についても検討したいと考えている。

E. 結論

1) ２０代と５０代の健康成人で歩行時の頭部運動および頭部と体幹の協調運動について３次元解析を行った。
2) ２０代５０代ともに歩行時頭部運動のうち、頭部上下動、pitch、roll 運動が開眼歩行時に比べて遮眼歩行時に有意に減少した。視覚入力が障害された場合、安定した歩行を継続するためには、耳石器や下肢深部知覚の感度を高める必要が生じ、頭部の鉛直性を保ち上下動揺を抑えるような歩行様式が選択されたものと考えられた。
3) ほとんどの２０代被験者で、歩行中頭部と体幹が逆方向に roll 運動を行っている所見（負の相関）がみられた。頭部、体幹 roll 運動が負の相関を示す被験者の場合、頭部と体幹の左右動は相殺され小さくなり、歩行中空間に対して頭部の安定が保たれている。また、遮眼歩行でも頭部、体幹協調運動のパターンが変わらないことは、中枢での空間識形成において前庭入力の関与が大きく視覚依存度が低いことを示していると考えられた。
4) ５０代被験者では、頭部と体幹が同方向に roll 運動する所見（正の相関）が多くみられた。この場合頭部の左右動揺が大きくなり、頭部は空間的に不安定になる。また、遮眼時に正の相関を示す被験者がさらに多くなることは、中枢における視覚依存度が高いことを示していると思われる。これらの所見は５０代健康成人の潜在的な前庭

機能の低下を示していると考えられた。

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F. 健康危険情報

なし

G. 研究発表

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H. 知的財産権の出願・登録状況

なし

別添4

厚生科学研究費補助金

感覚器障害及び免疫・アレルギー等（感覚器障害研究分野）研究事業

I．総括・分担研究報告

3. Effects of Aging on The Head and Trunk Movements During Walking

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Yasuhiko Takei (Saitama Municipal Hospital)

Abstract In order to evaluate the effects of aging on the head and trunk movements during locomotion, healthy adults with no history of vertigo or pediatric disorders consisting of 10 each in 20's (mean age 24.9 years), 50's (mean age 53.0 years), 60's (mean 64.8 years), and 70's (mean age 73.2 years) were examined kinesiologically during walking with their eyes open (EO) and with eye closed using an eye mask (EC). For this study, a 3-D motion analyzing system composed of 2 infrared digital CCD cameras and a data processor was used.

In all age levels of the 20's, 50's, 60's and 70's, vertical movements and pitch and roll movements were significantly smaller during walking with EC than with EO. Thus, we speculated that visual deprivation impairs spatial orientation in the brain resulting in a changed locomotor pattern, and that this may enhance the sensitivity of the other sensory systems.

In most of the subjects in 20's, the head roll was compensatory for the trunk roll (negative correlation) during walking both with EO and EC. In many of those in 50's and above, by contrast, the head and trunk moved in the same direction (positive correlation) during walking especially with EC. The findings in the present study suggest that in young people the center of gravity is better stabilized during walking than in older people, and that young people are less dependent on visual input for spatial orientation in the brain than older people.

A. Purpose

Numerous studies have examined the neurological and dynamic features of walking.[1,2] A large number of analyses of linear movements such as vertical and lateral movements of various parts of the body during walking have been carried out, but actual measurement of rotational movements of the head was first made in 1988 by Grossman et al., who measured yaw movements and pitch movements of the head during walking in place using search coils system.[3] Thereafter, as motion analysis systems utilizing new image processing techniques, such as the infrared CCD camera and 16-mm high-speed camera, have been developed, high-precision analysis of walking has become possible even during free walking and walking on a treadmill.[4-12] We have also analyzed head movements in humans walking on the floor using a three-dimensional motion analysis system incorporating infrared digital CCD cameras, and reported findings primarily in younger people.[18]

Recently, accidental falling of the elderly has become a social issue, and the objective evaluation of the stability during walking is expected to become more important in the future. Concerning changes in walking movements with aging, there have been many studies primarily using parameters including the stride, pace, joint angle, ground-contact time, and leg-swing time.[14-17] In this study, we performed three-dimensional analysis of head movements (vertical movements and rotational movements on the pitch, roll, and yaw planes) during walking in healthy adults in 20's, 50's, 60's, and 70's to evaluate the effects of aging on walking movements from the viewpoint of vestibular function. We further analyzed coordination of head and trunk movements and compared it among various age levels.

B. Methods

Healthy adults with no history of vertigo or pediatric disorders consisting of 10 each in 20's (mean age 24.9 years), 50's (mean age 53.0 years), 60's (mean 64.8 years), and 70's (mean age 73.2 years) were selected as the subjects.

The measurements were carried out in our hospital hallway about 4 m wide (Fig. 1a). Five infrared reflection markers were placed on the body of the subjects. They wore a headgear with markers attached to the parietal region (M1), and left (M2) and right (M3) posterior temporal regions, and markers were attached also to the vertebra prominens (M4) and the waist (M5) (Fig. 1b). The subjects were positioned at the starting point and instructed to walk straight for 5 seconds (about 5-9 steps, 4-7 m in distance) after a signal given by an examiner. They walked 5 times at first with the eyes open (EO) then 5 times with the eyes closed using an eye mask (EC). They were instructed to look straight ahead and walk at a normal speed without setting a visual mark or a recommended pace. In walking with the eyes closed, the subjects were led back to the starting point after each walk so as not to give them feedback information.

The measurements of the head movements and data analysis were performed using the three-dimensional motion analysis system Mac Reflex^{R} of QUALISYS. This system, which consisted of 2 infrared digital CCD cameras, a processor, and a motion analysis software, converted the three-dimensional position of the infrared reflection markers attached to the body into three-dimensional coordinates (Fig. 1a). Prior to the measurements, the coordinates were calibrated so that the direction of walking (anterior-posterior direction of the body) was set as the Y axis, the horizontal direction perpendicular to the Y axis (left-right direction of the body) as the X axis, and the vertical direction as the Z axis. Measurements were performed for 5 seconds at 60 Hz. The optical error of measurements using a Mac Reflex in the calibration frame was 0.003% of FOV (field of view).

Figure1a) Experiment setup. Infrared digital CCD cameras installed in two places of rear of a subject and the computer for analysis: A subject walks to orientation going away from cameras.

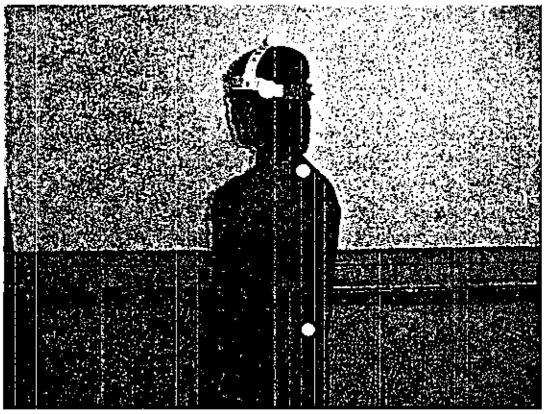


Figure1b) Infrared reflection markers attached to the parietal and both posterior temporal regions of a headgear, the vertebra prominens and the waist totaled 5 places

[Parameters]

The following parameters were used for the analysis of head movements during walking.

(1) Vertical head movements: Vertical movements (mm) of the marker in the right posterior temporal region (M3).

(2) Pitch rotational movements of the head: The range of changes in the angle (deg) between the Z axis and the line from the midpoint of the bilateral posterior temporal markers (M2 and M3) to the parietal marker (M1) (Fig. 2a).

(3) Roll rotational movements of the head: The range of changes in the angle (deg) between the Z axis and the line between the bilateral posterior temporal markers (M2 and M3) (Fig. 2b).

(4) Yaw rotation movements of the head: The range of changes in the angle (deg) between the X axis and the line between the bilateral posterior temporal markers (M2 and M3) (Fig. 2c).

In this study, the following parameters were also calculated to evaluate coordination of head and trunk movements.

(5) Roll rotational movements of the head and trunk: The degree between the Z axis and the line between the parietal marker (M1) and the marker at the vertebra prominens (M4) and the degree between the Z axis and the line between the marker at the vertebra prominens (M4) and the waist marker (M5) were determined, and they were compared in the same time course (Fig. 3).

(6) Lateral movements of the head and trunk: Lateral movements of the parietal marker (M1), marker at the vertebra prominens (M4), and waist marker (M5) were measured and compared in the same time course.

The significance of differences between groups or between different visual conditions were examined by t-test.

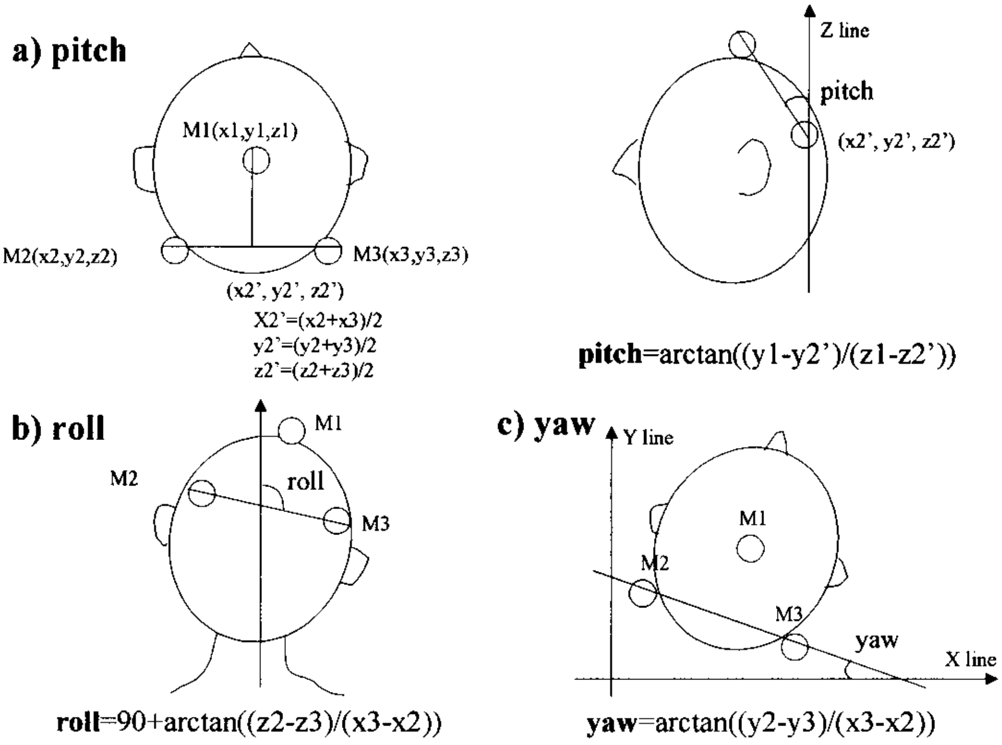


Figure2 Calculation methods of pitch, roll, and yaw angle of the head

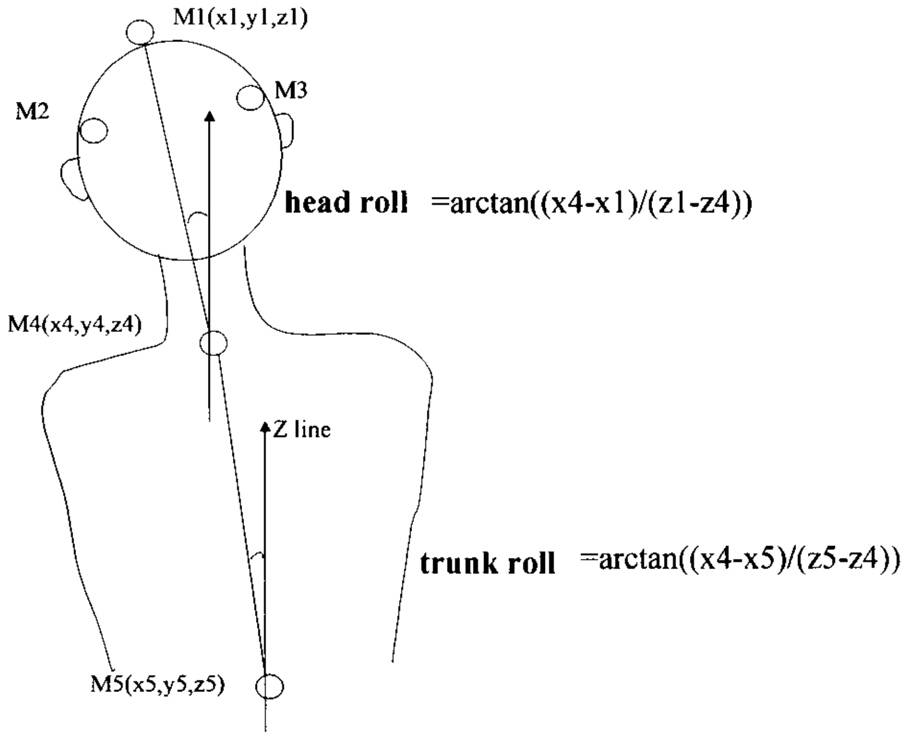


Figure3 Calculation method of roll angle of the head and trunk

C. Results

I. Head movements during walking

1) Vertical movements of head (Fig. 4a)

The mean vertical movements of the head was 46.0±14.5 mm with the eyes open (EO) and 36.3±9.8 mm with the eyes closed (EC) in the subjects in 20's, 50.5±9.0 mm and 46.4±9.5 mm, respectively, in those in 50's, 45.9±6.1 mm and 38.6±6.0 mm, respectively, in those in 60's, and 39.6±7.2 mm and 33.5±7.4 mm, respectively, in those in 70's. Vertical movements of the head were significantly smaller with EC than with EO in each age level. No significant difference was observed among the age levels with EO or with EC. Vertical head movements showed no significant difference when they were calculated using any of the 3 head markers (M1-3).

2) Pitch rotational movements of head (Fig. 4b)

The mean range of pitch rotation of the head was 4.8±1.2 deg with EO and 3.7±0.8 deg with EC in the subjects in 20's, 4.2±0.9 deg and 3.4±0.7 deg, respectively, in those in 50's, 4.2±0.9 deg and 3.4±0.5 deg, respectively in those in 60's, and 4.0±0.7 deg and 3.5±0.4 deg, respectively, in those in 70's. Pitch movements of the head during walking were significantly smaller with EC than with EO in each age level. No significant difference was observed among the groups with EO or EC.

3) Roll movements of head (Fig. 4c)

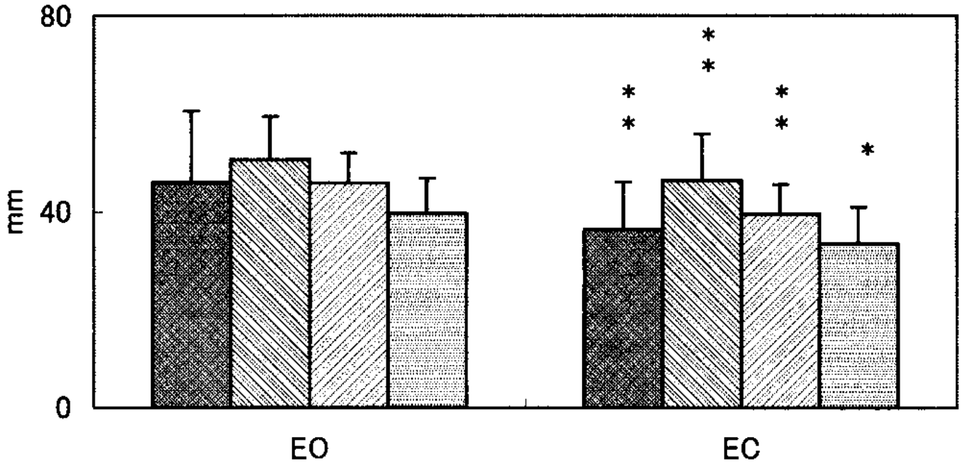
The mean range of roll rotation of the head was 4.0±1.4 deg with EO and 2.4±0.5 deg with EC in the subjects in 20's, 4.6±2.2 deg and 3.0±0.8 deg, respectively, in those in 50's, 4.6±0.9 deg and 3.0±0.6 deg, respectively, in those in 60's, and 3.9±1.0 deg and 2.7±0.5 deg, respectively, in those in 70's. Roll movements of the head during walking were significantly smaller with EC than with EO at each age level. No significant difference was observed among the groups with EO or EC.

4) Yaw movements of head (Fig. 4d)

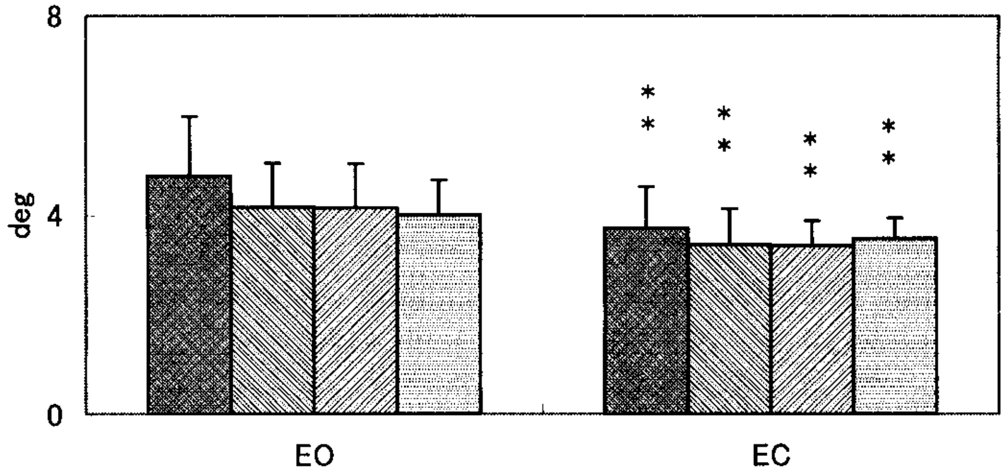
The mean range of yaw rotation of the head was 3.5±0.7 deg with EO and 3.6±0.5 deg with EC in the subjects in 20's, 4.0±1.3 deg and 3.7±1.0 deg, respectively, in those in 50's, 3.6±0.5 deg and 3.9±0.8 deg, respectively, in those in 60's, and 3.4±0.4 deg and 3.7±0.6 deg, respectively, in those in 70's. Yaw movements of the head during walking showed no significant difference between with EO and EC or among the groups.

Figure4 Head movements during walking with the eye open (EO) and with the eye closed (EC) of healthy adults of 20's, 50's 60's, and 70's (mean ± 1SD)

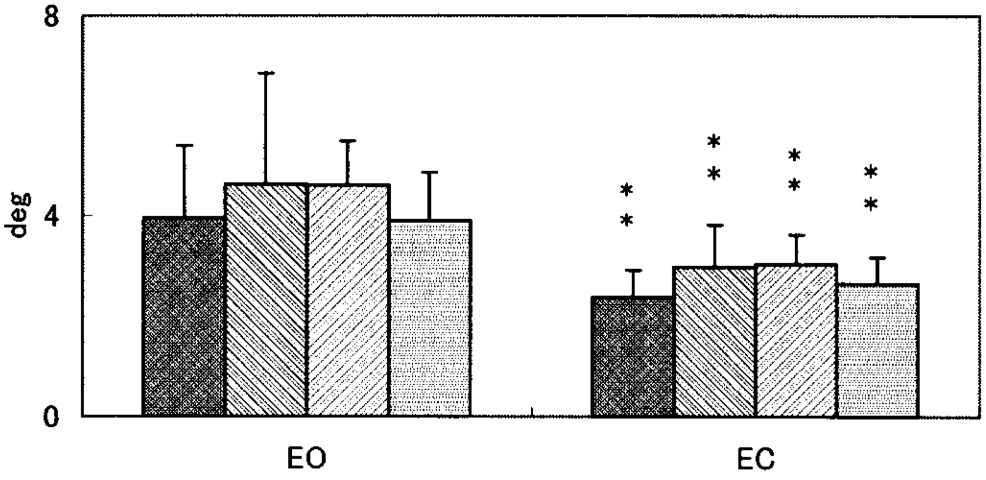
a) vertical movements



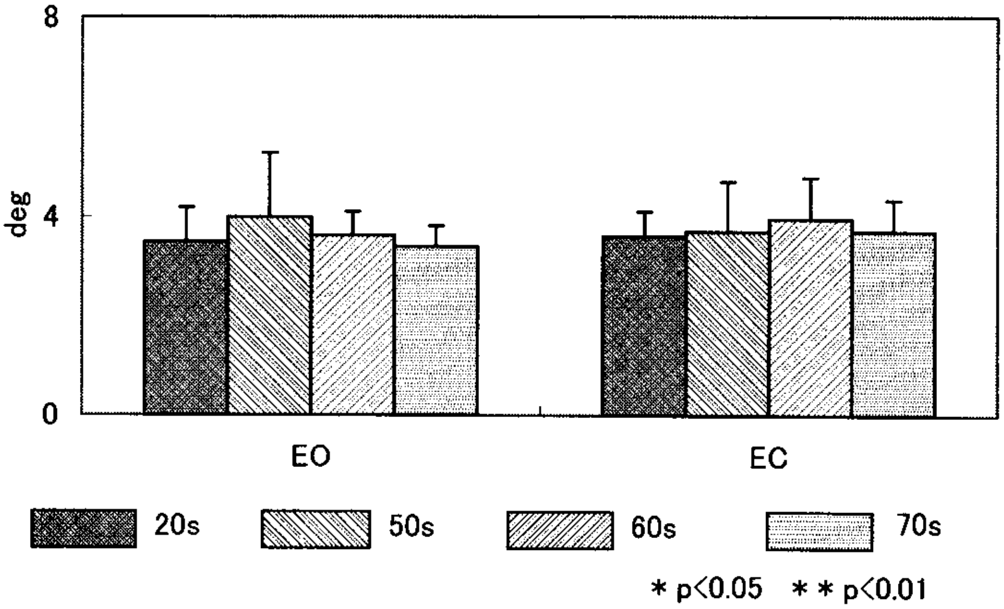
b) pitch



c)roll



d) yaw



II. Coordination of head and trunk movements

1) Roll movements of head and trunk

The upper panels of Fig. 5a and 5b show serial changes in roll movements of the head and trunk during walking in typical subjects in 20's and 50's. The lower panels of Fig. 5a and 5b are scattergrams representing the correlation of roll movements of the head and trunk.

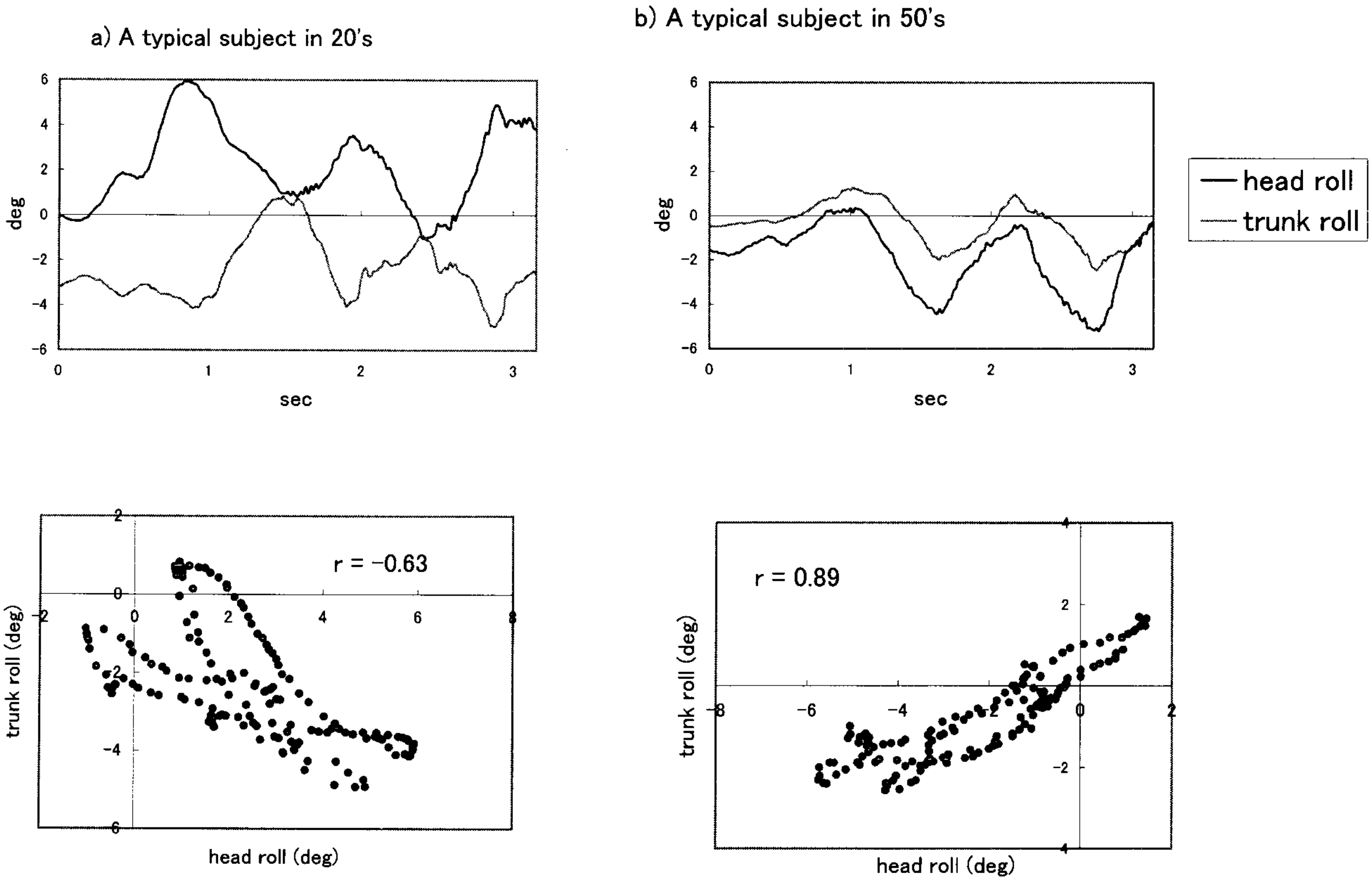
Most subjects in 20's exhibited coordination of opposite roll movements between the head and trunk during walking as observed in the upper panel of Fig. 5a. Thus, in the scattergram, a negative correlation was observed in roll movements between the head and trunk. The correlation coefficient in this subject was -0.63 (Fig. 5a, lower panel).

In many subjects in 50's, the head rolled in the same direction as the trunk as in Fig. 5b, and roll movements of the head and trunk showed a positive correlation. In this subject, the correlation coefficient was 0.89 (Fig. 5b, lower panel).

The correlation coefficient between roll movements of the head and those of the trunk was calculated in all subjects of all age levels and compared (Fig. 6).

A negative correlation was observed in 9 of the 10 subjects in 20's both with EO and with EC (Fig. 6a). However, a positive correlation was observed in 4 of the 10 subjects in 50's with EO. With EC, the correlation changed to positive in 3 of those who showed a negative correlation with EO, and a total of 7 subjects showed a positive correlation (Fig. 6b). Of the 10 subjects in 60's, 3 showed a positive correlation with EO. With EC, the correlation changed to positive in 2 of those who showed a negative correlation with EO, and a total of 5 subjects showed a positive correlation (Fig. 6c). Of the 10 subjects in 70's, 3 showed a positive correlation with EO. With EC, the correlation changed to positive in 3 of those who showed a negative correlation with EO, and a total of 6 subjects showed a positive correlation (Fig. 6d).

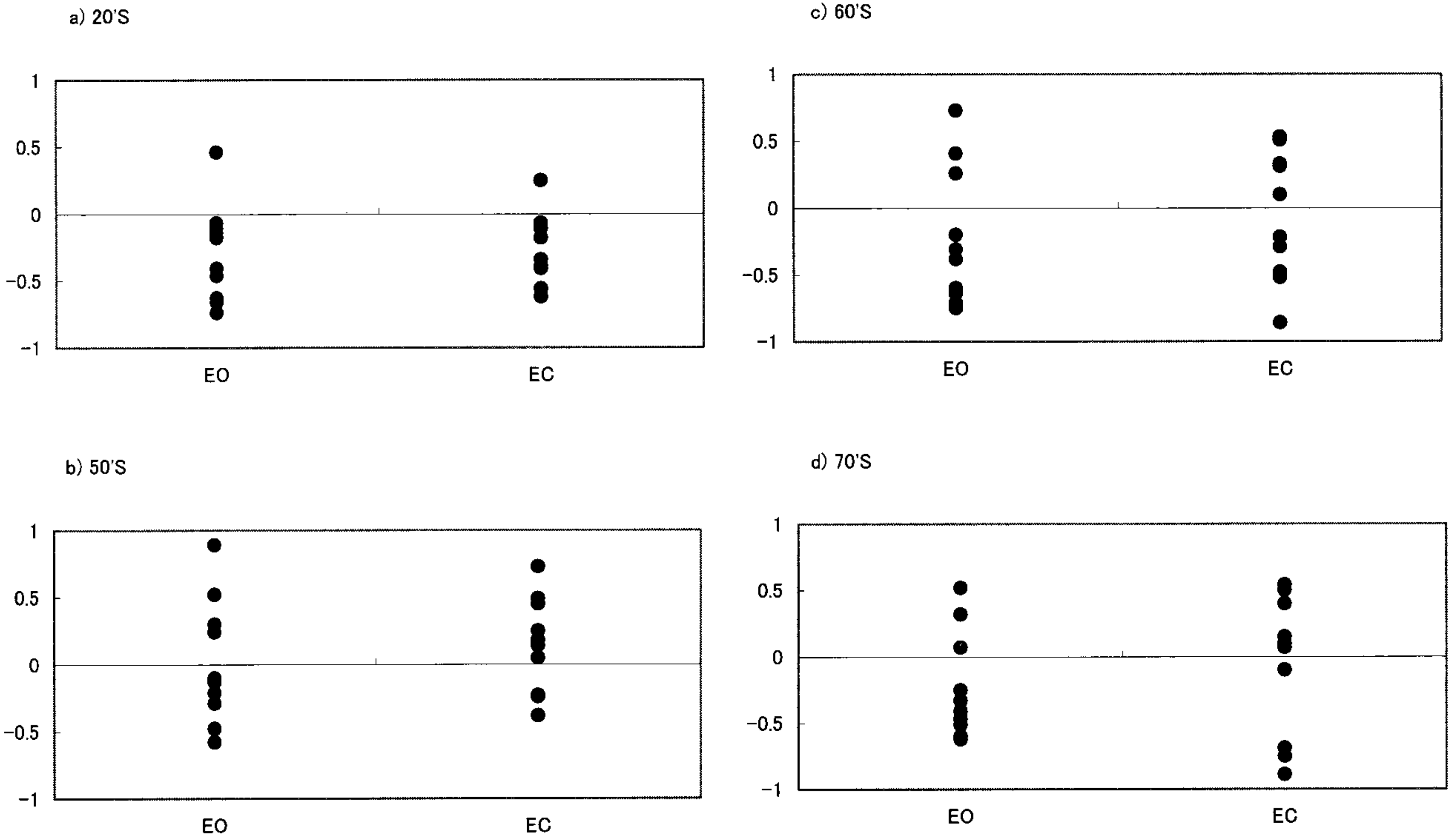
Figure5 Roll movements of head and trunk



a) A typical subject in 20's

b) A typical subject in 50's

Figure6 Correlation coefficient between roll movements of head and trunk


a) 20'S

c) 60'S

b) 50'S

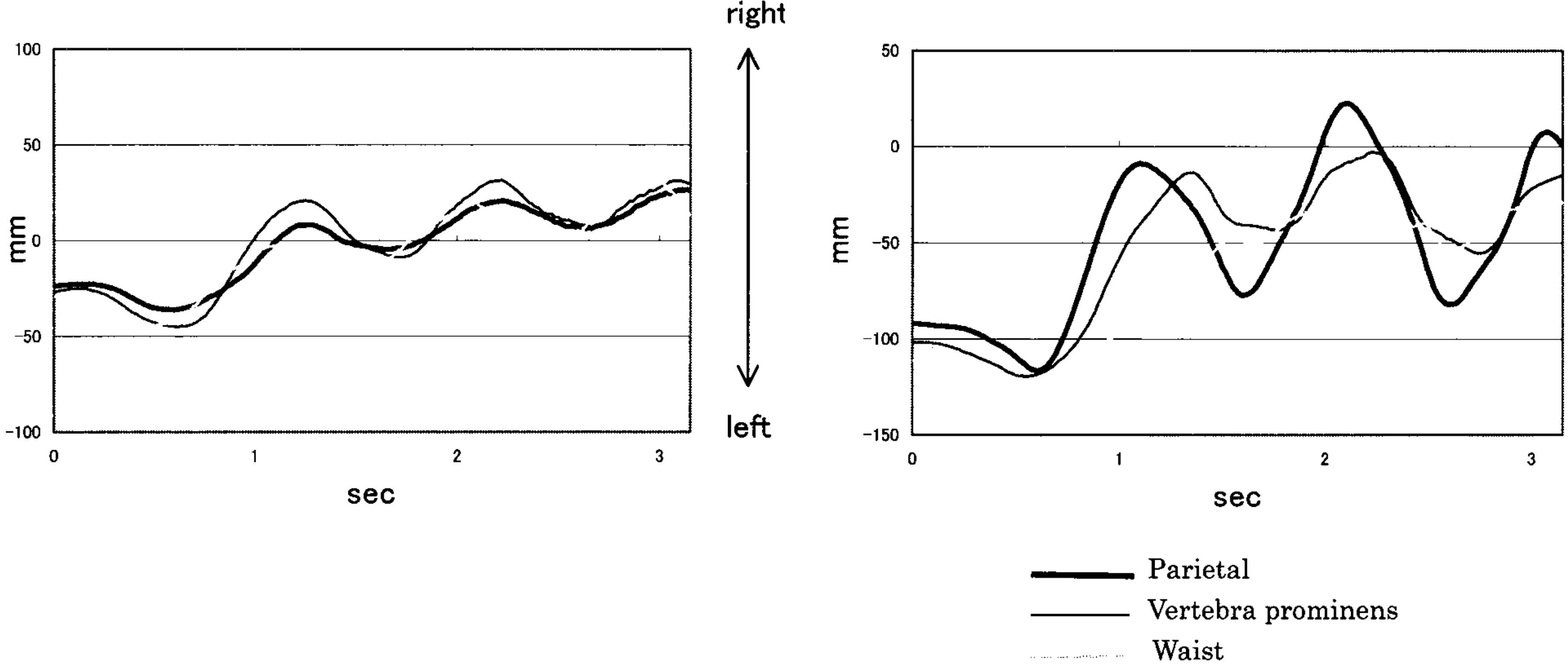
d) 70'S

2) Lateral movements of head and neck

Fig. 7 compares lateral movements of the parietal region, vertebra prominens, and waist during walking with EO in typical subjects in 20's and 50's in the same time course. In the typical subject in 20's who showed a negative correlation in roll movements between the head and trunk (opposite roll movements of the head and trunk), the lateral movements of the parietal region were smaller than those of the vertebra prominens (Fig. 7a). However, in the typical subject in 50's who showed a positive correlation in roll movements between the head and trunk (roll movements of the head and trunk in the same direction), lateral movements of the parietal region were larger than those in the vertebra prominens (Fig. 7b). Therefore, lateral movements of the parietal region tended to be greater in the subjects who showed a positive correlation in roll movements of the head and trunk than in those who showed a negative correlation.

Fig. 8 shows the mean lateral movements of the parietal region, vertebra prominens, and waist in the subjects in 20's, those in 50's, 60's, and 70's who showed negatively correlated roll movements of the head and neck and those in 50's, 60's, and 70's who showed positively correlated roll movements. In the subjects of all age levels who showed negatively correlated roll movements, lateral movements of the parietal region, vertebra prominens, and waist were not significantly different from those of subjects in 20's both with EO and with EC. However, lateral movements of the parietal region during walking with EO were significantly larger in the subjects in 50's, 60's, and 70's who showed positively correlated roll movements than in the subjects in 20's. No significant difference was observed in lateral movements of the vertebra prominens or the waist among the groups during walking with EO. During walking with EC, lateral movements of the parietal region, vertebra prominens, and waist were all greater in the subjects in 60's and 70's who showed positively correlated roll movements than in the subjects in 20's. No significant difference was observed in lateral movements of the parietal region, vertebra prominens, or waist during walking with EC between the subjects in 50's who showed positively correlated roll movements and those in 20's.

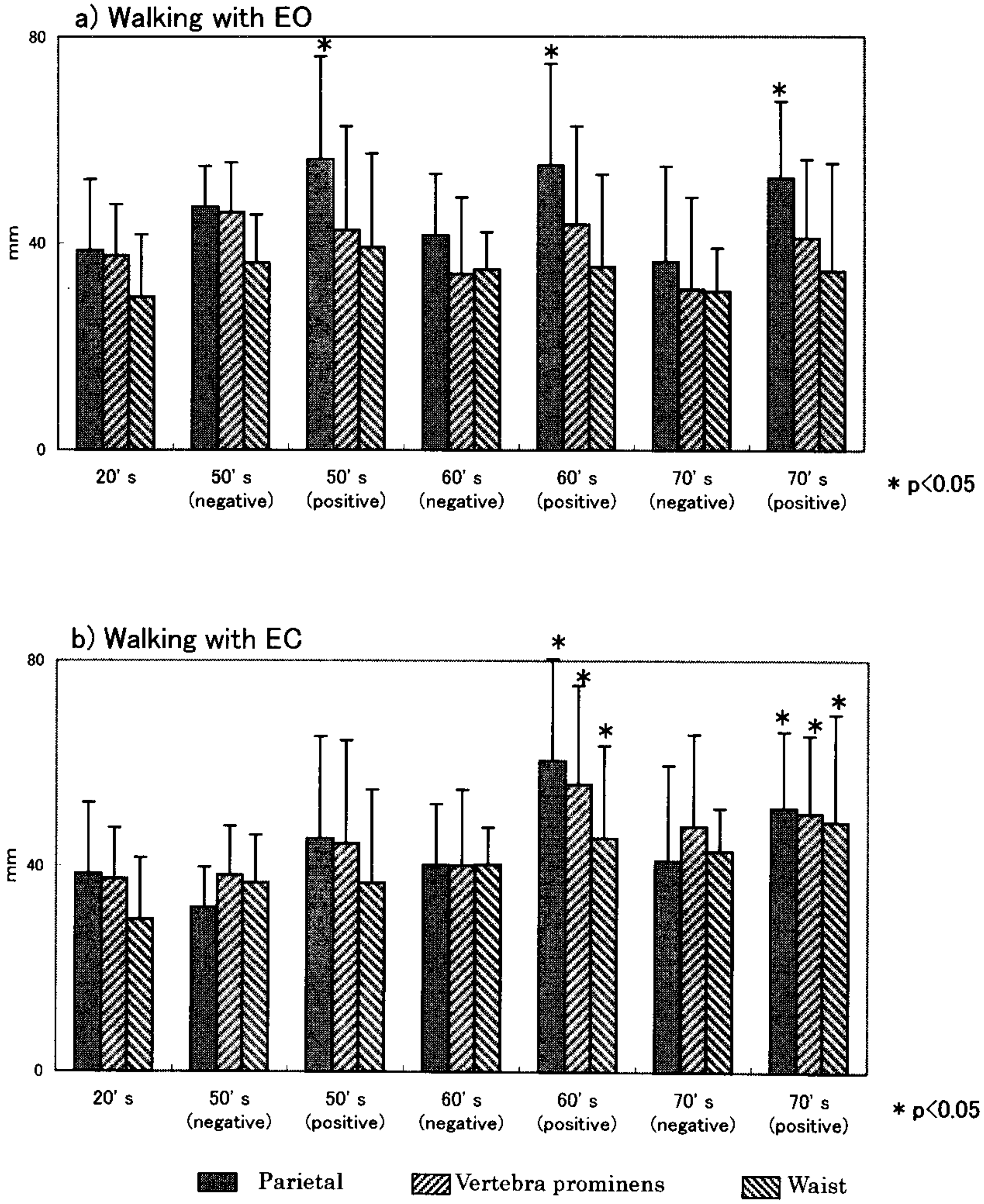
Figure7 Lateral movements of the parietal region, vertebra prominens, and waist during walking with EO in typical subjects in 20’s and 50’s



a) A typical subjects in 20’s who showed a negative correlation

b) A typical subjects in 50’s who showed a positive correlation

Figure8 Lateral movements of the parietal region, vertebra prominens, and waist during walking in the subjects in 20's, 50's, 60's, and 70's (mean ± 1SD)



D. Discussion

I. Stabilization of the head during walking

For instantaneously maintaining the body balance in daily activities including walking, motion control in the brain on the basis of the spatial orientation is necessary. The spatial orientation is recognition of the relative spatial relationship between the self and the surrounding space and is accomplished by reproducing the surrounding three-dimensional space in the brain by integrating multiple sensory inputs.[18,19]

In this study, vertical movements and pitch and roll movements of the head during walking were significantly smaller with the eyes closed than with the eyes open in all age levels of the 20's, 50's, 60's, and 70's, but no difference was observed in yaw movements. From these results, it is guessed that suppression of vertical perturbation and preservation of the verticality of the head are important for maintaining stable gait in the absence of visual information.

When the eyes are closed, the spatial orientation becomes incomplete, and gait control is disrupted. To increase the precision of spatial orientation and maintain stable walking movements, the sensitivity of sensory inputs other than visual input must be enhanced. The sensitivity of the otolith organ (macula of utricle) is maximum when the otolith membrane is positioned horizontal level with the direction of acceleration.[4] Therefore, it is considered that the walking pattern in which vertical perturbation of the head is reduced and the verticality of the head is maintained have been selected when the eyes were closed to increase the sensitivity of the otolith organ which detects acceleration in the direction of movement. This is considered to be part of the evidence that supports the presence a mechanism to stabilize the walking posture primarily by stabilizing the head position (top-down control).[2,4]

II. Effects of aging on head and trunk movements during walking

Many gait analyses to date have detected coordination of head and trunk movements in healthy adults: The head shows pitch movements, or anterior flexion when the head position is elevated and posterior flexion when the head position is lowered;[4-7,9-11] when one foot is on the ground, the trunk shows roll movements to the side of this foot and the head shows roll movements to the opposite side.[7-10,12] Similar coordinated movements were observed also in our previous gait analyses primarily in young subjects.[13] These rotational movements of the head during walking have physiologic significance of maintaining the stability by reducing the perturbation of the center of gravity during walking.

In the present study, also, coordination between vertical movements and pitch movements of the head was observed similarly in the subjects of all age levels. However, differences were observed in head and trunk roll movements between the subjects in 20' and those in 50's or older. While most of the subjects in 20's showed coordinated movements in which the head and trunk rolled in opposite directions (negative correlation) during walking as reported earlier, many of those aged 50 years and above showed rolling of the head and trunk in the same direction (positive correlation). Assaiante et al.[7] performed gait analysis in children aged 3-8 years and observed positive correlation of roll movements of the head and trunk in many subjects. Mesure et al.[12] also reported a positive correlation in roll movements between the head and trunk during walking in patients with Parkinson's disease. Positive correlation of roll movements of the head and trunk is not explained simply by underdevelopment or a reduction of muscle strength or an enhancement of muscle tone, because coordination between vertical movements and pitch movements was observed in the elderly subjects of this study, children reported by Assaiante et al., and patients with Parkinson's disease reported by Mesure et al. as well as in healthy adults.

In the subjects who showed a negative correlation in roll movements of the head and trunk, lateral perturbation of the head and trunk was reduced as they were cancelled by each other, so that the stability of head relative to the space during walking was maintained. Also, in most subjects in 20's, the pattern of coordination between head and trunk movements remained negative also in walking with the eyes closed. This suggests that the formation of the spatial orientation in the central nervous system depends highly on vestibular inputs and not