Relationship between head control ability and step leg hip kinematics during crossover steps in older individuals

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Abstract

This study aimed to investigate the characteristics of lateral stepping in response to disturbance loading in relation to kinematic factors of the step leg hip by evaluating head stability and righting ability during crossover steps. The participants comprised 11 healthy older individuals and 13 younger individuals (mean age, 73.3 and 20.2 years, respectively). An electromagnet-controlled disturbance loading device caused crossover steps due to lateral disturbance which were measured using a motion capture system and force plates. The extent of lateral head sway was found to be significantly greater and the angle and angular velocity of head righting were significantly lower in the older individuals than in the younger individuals. A significant negative correlation was found between neck lateral flexion moment and hip flexion angular velocity of the step leg in both groups. Correlation analysis between cervical lateral flexion moment and hip adduction angular velocity showed a significant negative correlation only in the older group. The results of the study indicate that during lateral stepping due to external disturbances, older individuals experienced increased instability in the lateral direction of the head and decreased righting angles and angular velocities.

Introduction

Falls in older individuals can lead to serious complications, and post-fall syndromes can further reduce activities of daily living and limit social participation. Among the postural control strategies [1] used when a person loses balance in the standing posture, the stepping reaction is the most effective reaction to prevent falls. The stepping reaction, in which the body is supported by expanding the base of support by stepping forward, is said to provide better mechanical stability compared to a reaction that tries to correct the body alignment around the ankle joint or hip joint [2]. Falls in older individuals are associated with postural stability in the lateral direction [3] and falls to the lateral direction result in a hard impact on the greater trochanter, often resulting in a femoral fracture [4–6]. Thus, there is a strong need to better understand the stepping reaction to the lateral direction. Three stepping patterns can expand the base of support to the lateral side: the crossover step, side step sequence, and loaded leg step [7]. The crossover step is a strategy often used by young adults to cope with lateral disturbance loads. However, it is difficult for older individuals to control the crossover step because this requires accurate movement of the step foot while avoiding contact with the supporting leg and maintaining one-leg support for a long period of time [8]. Thus, it is crucial to focus on the crossover step, which is an important stepping reaction for the recovery of balance in the lateral direction and whose control becomes more difficult with age.

In addition, the stepping reaction involves a shift in the center of mass of the whole body as the foot steps forward to expand the base of support, and in the crossover step, the ankle joint or hip joint of the supporting leg becomes the center of rotation. The body segment most distal to the center of rotation is the head, where receptors important for balance, such as hair cells sensing rotational acceleration in semicircular canals and linear acceleration in the utricle and saccule due to otolith movements, are located. Input from this vestibular system influences postural tone. Vestibular input is activated by
changes in head localization, causing changes in the distribution of postural tone in the neck and extremities [9]. This has been called the vestibulocervical or vestibulospinal reflex.

When a person loses balance in the standing posture, a righting reaction to keep the head vertical in space occurs. This induces a righting reaction in the trunk, leading to the formation of a new base of support by stepping of the lower limbs. To understand the mechanism of balance recovery by crossover stepping, it is important to investigate how the center of mass of the head is controlled and positioned in space during the stepping movement. Furthermore, based on the aforementioned vestibulocervical and vestibulospinal reflexes, it is imperative from the perspective of fall prevention in older individuals to investigate the effects of head and trunk position changes during the step movement on lower limb joint movements that expand the base of support, as well as their age-related changes.

This study aimed to investigate the head control ability of older individuals based on the amount of head swaying and the righting angle and angular velocity during the crossover step, a lateral stepping reaction. Moreover, we examined the lateral neck moments that control the head position and investigated the factors involved in head control during crossover steps. In addition, we aimed to investigate the relationship between these factors involved in head control and the angular velocity of flexion and adduction of the step leg hip joint, a kinematic factor of crossover steps.

Methods

Participants

Eleven healthy older individuals (mean age, 73.3 ± 3.8 years, 3 women) living in the community were enrolled as study participants, and 13 healthy young individuals (mean age, 20.2 ± 0.6 years, 11 women) were selected as the control group. All 24 participants had no known major orthopedic or neuromuscular diseases or physical disability. Participants were included in the study if they were able to perform a crossover step in response to lateral disturbances while standing.

All participants were informed of the purpose of the experiment in writing and orally, and All participants provided written informed consent form. This study was approved by the Ethical Review Committee of Chiba Prefectural University of Health Sciences. All experiment were performed in accordance with the guidelines of the committee and with the Declaration of Helsinki.

Lateral direction disturbance loading

Figure 1 shows an overview of the disturbance load device. An electromagnetically controlled standing disturbance loading device (S-17164, Takei Kiki Kogyo Co., Ltd.) was used for lateral direction disturbance loading. This device was connected to a load sensor worn by the participant and a traction wire connected to electromagnets. When the traction load exceeded an arbitrary setting, the electromagnets were demagnetized, and the traction wire was disconnected from the electromagnets to cause a disturbance.
The participant maintained a standing posture with the right and left feet each positioned on one of two rows of force plates (AMTI, BP400600), with the medial edges of both sides 15 cm apart. The participants were instructed to gaze at an index 2 m in front of them. From this posture, the center of mass was moved voluntarily to the left, and the participant was exposed to a disturbance when a load of 10% of the participant's body weight was applied from the traction wire to the load sensor (Fig. 1). The length of the traction wire was standardized among the participants so that the tilt angle of the participant's body when the disturbance was applied was standardized as much as possible.

Measurement device

A three-dimensional motion analyzer (Motion Analysis, Mac3D system) consisting of eight infrared cameras and a force plate was used to measure the lateral direction step reaction. Based on the Helen Hayes marker set [10], 19-mm diameter infrared reflective markers were placed on 25 points on the participants’ bodies. The sampling frequencies for both the infrared camera and the force plate were set to 100 Hz. Signals from the infrared camera, force plate, and disturbance loader were synchronized via an AD converter connected to a personal computer during data acquisition.

Data analysis

The analysis section was defined as the period from the time when the lateral disturbance was applied to the time when the step foot landed on the ground. The timing of the start of the disturbance loading was identified by the signal from the disturbance loading device, and the timing of the landing of the step foot was identified from the vertical direction floor reaction force value of the landing side force plate.

Motion analysis software (C-motion, Visual3D) was used to analyze the data. Segmental models of the head and torso were created from the camera-derived point data, and the position of each center of mass was calculated using Winter's method [11]. The effective acceleration value of the center of mass of the head in the analyzed segment was defined as the amount of sway of the head and was calculated for each of the interior-posterior, lateral, and vertical directions. The tilt angle and angular velocity of the center of mass of the head and trunk relative to the vertical axis on the frontal plane were also calculated and defined as the righting angle and angular velocity (Fig. 2). In addition, the lateral bending moment of the neck and the angular velocity of hip flexion and adduction at the time of step emergence were calculated for the analyzed section, and the maximum value of each parameter was used. The lateral bending moment of the neck was defined as the center of rotation at the seventh cervical vertebra, the external moment was calculated as the product of the floor reaction force value and the distance from the center of rotation to the floor reaction force action line, and the internal moment was calculated as the opposing force. The positive value for the lateral bending moment of the neck was the lateral direction opposite to the direction of the external disturbance. The hip angular velocity was calculated for the hip joint of the step leg, with positive values for forward flexion and leftward adduction (step direction).

Statistical analyses were performed to compare the amount of sway of the head center of mass in each direction, the tilt angle and angular velocity of the head/trunk center of mass, as well as the neck lateral
flexion moment and hip flexion/adduction angular velocity of the step leg, between the older and younger groups using Welch's t-test. In addition, Pearson's reserve correlation coefficient was used to analyze the relationship between the neck lateral flexion moment and the hip flexion/adduction angular velocity of the step leg. The significance level was set at 5%.

Results

Amount of sway of the center of mass of the head

Table 1 shows the amount of sway of the center of mass of the head in each direction during the crossover step. The values were significantly higher in the left-right direction, which is the direction of disturbance, in the older group than in the younger group (p<0.01). There was no significant difference between the two groups in the anterior-posterior and vertical directions.

Righting angle and angular velocity of the center of mass of the head and trunk

Table 1 also shows the righting angles and angular velocities of the head during the crossover step. Significantly lower head values were noted in the older group than in the younger group for both righting angle and angular velocity.

For the trunk, there were no significant differences in righting angle and angular velocity between the two groups.

Cervical lateral bending moment

Table 1 shows the lateral bending moment of the neck during the crossover step. The values were 2.5±1.5 Nm/kg for the older group and 0.7±0.4 Nm/kg for the younger group, showing significantly higher values in the older group.

Angular velocity of flexion and adduction of the hip joint of the step leg

The angular velocity of hip flexion was 38.3±22.5 deg/s in the older group and 18.5±10.7 deg/s in the younger group, that is, this parameter was significantly higher in the older group. The angular velocity of adduction was 213.2±67.9 deg/s in the older group and 202.3±57.4 deg/s in the younger group, showing no significant difference between the two groups.
Relationship between cervical lateral bending moment and hip angular velocity

Correlation analyses between cervical lateral flexion moment and hip flexion angular velocity showed significant negative correlations in both older ($r=-0.61, p<0.05$; Fig. 3) and younger ($r=-0.55, p<0.05$; Fig. 4) groups. Similar correlation analyses of cervical lateral flexion moment and hip adduction angular velocity showed a significant negative correlation only in the older group ($r=-0.71, p<0.01$; Fig. 5).

Discussion

The results of this study confirmed that during the lateral step reaction, the extent of sway of the center of mass of the head was significantly larger in the lateral direction, which was the direction of the disturbance load, in the older group than in the younger group. In this study, the effective acceleration value of the center of mass of the head was defined as the amount of sway. This indicates that the ability to control the acceleration of the head in the left-right direction during the lateral step reaction caused by a disturbance is decreased in the older group. A previous study [12] that investigated the acceleration of the head during step reactions in response to frontoposterior disturbances reported that the linear acceleration of the head in the frontoposterior direction was significantly greater in the older group than in the younger group. Age-related degeneration and atrophy of the peripheral vestibular system extend throughout the entire vestibular apparatus from otoliths and hair cells to the vestibular nerve [13, 14]. Similar to these findings in the anterior-posterior direction, the results of the current study confirm that during the lateral step reaction, the linear acceleration of the head in the lateral direction is greater in older individuals.

In addition, the results for the righting angle and angular velocity of the center of mass of the head showed that both parameters were significantly lower in the older group than in the younger group. This indicates that the reaction to an antigravity position, which aims to quickly reestablish the head center of mass that had been tilted toward the disturbance direction back to a vertical position in space, is reduced during the period from the time of disturbance loading to the landing of the step foot.

The vestibular organ (semicircular canals, as well as saccule and utricle), which contains receptors for equilibrium sensation, senses the acceleration of the head and sends this information to a type of neural integrator called the neural store [15]. In addition to vestibular sensory information, somatosensory information (perception information) and visual information are integrated and processed in the neural store to calculate the appropriate output to the musculoskeletal system. When older individuals lose their balance in the standing posture and recover their balance without falling, the head and trunk remain vertically in space, which reduces the acceleration generated in the vestibular organ and leads to a step reaction in the lower limbs. In case of a fall, however, a reduced righting of the head leads to greater head acceleration, due to increased neck and trunk muscle activity brought about by the vestibulospinal reflex. This causes the head and trunk to act as one mass and tilt as the head did. As a result, the step reaction
of the lower limbs does not occur, and finally, the center of mass is displaced from the base of support, leading to a fall [3].

All older participants in this study were able to initiate a sideward step reaction (crossover step) in response to the disturbance load. However, the aforementioned results in older individuals showed that the acceleration of the center of mass of the head in the left-right direction was significantly increased, whereas both righting angle and angular velocity of the head were decreased. This suggests that the reduced righting ability of the head to reduce the head acceleration may also delay the initiation of the stepping reaction due to the vestibular organ sensing the acceleration and increasing the stiffness of the torso and lower extremities.

The results of the cervical lateral bending moments during the lateral stepping reaction showed that the older group generated significantly larger moments than the younger group. This moment is the source of the head righting force in older individuals, in which the neck bends in the lateral direction opposite to the direction in which the disturbance occurs, i.e., the head is held in a vertical position in space. The results of this study showed no significant differences between the two groups in the righting angle and angular velocity of the center of mass of the torso. Therefore, the involvement of the torso in the reactive head righting opposite to the direction of disturbance may be small, and greater involvement of the neck lateral bending moment in adjusting the position of the head in space may be a characteristic of older participants. Contrarily, the righting angle and angular velocity values of the center of mass of the head opposing the disturbance direction were significantly lower in the older than in the younger group. In combination with the results of the aforementioned cervical lateral direction moment, it is clear that older individuals generated greater rotational forces in the direction opposite to the disturbance direction, but the head righting angle and its speed were lower. The cervical lateral flexion moment is used as an index in this study. This internal moment is the product of the muscle contraction force and the distance between the line of the floor reaction force and the seventh cervical vertebra as the center of rotation. Therefore, it reflects the contractility of cervical lateral flexor muscles such as the right sternocleidomastoid and oblique muscles. This suggests that older individuals control the displacement of the head in the lateral direction by strongly contracting the cervical lateral flexor muscle group in response to the disturbance load. Since the joint moments exerted during neck lateral flexion were calculated and used as indices in this study, it is necessary to verify in future studies the specific muscle groups involved in neck righting movements, including the amount of activity and contraction patterns of the cervical lateral flexor muscles.

The results of the angular velocity of flexion and adduction of the supporting leg hip showed significantly higher flexion values in the older group than in the younger group. In other words, older individuals swung their stepping leg faster forward when the disturbance-induced stepping reaction occurred. Older people often use the side-step sequence in which the lower limb on the side of the disturbance takes a lateral step. The crossover step, the task movement in this study, is considered a more difficult reaction than the side-step sequence because the step leg crosses in front of the supporting leg [3, 7, 8]. The results of the
present study suggest that older individuals increased the angular velocity of hip flexion at the onset to avoid contact between the stepping leg and the supporting leg.

The results of the correlation analyses between cervical lateral flexion moment and hip flexion angular velocity showed a significant negative correlation in both groups. This indicates that the participants who demonstrated greater cervical lateral flexion moments had slower hip flexion angular velocities. Considering the aforementioned theory [3] of the relationship between neck muscle activities and lower limb stiffness, a stronger cervical lateral flexion moment or muscle contraction of the cervical lateral flexor muscle group causes the head and trunk to become one fixed mass, thereby increasing head acceleration. As an effect of aging, the vestibular organ senses the stronger head acceleration, which increases the muscle activities and stiffness of the lower limbs, decreases the angular velocity of flexion of the step leg hip joint during disturbance loading, and further decreases the angular velocity of adduction to generate a new base of support in the direction of disturbance loading.

**Conclusions**

The results of this study indicate that the amount of lateral head swaying is greater in older participants during disturbance-induced lateral stepping whereas the ability to recover the head position in space in response to external disturbance is reduced. It was also found that the lateral bending moment of the neck was significantly increased as a strategy to correct the head position opposite to the direction of disturbance. Moreover, the lateral bending moment of the neck was significantly negatively correlated with the angular velocity of hip flexion of the stepping leg. These results indicate that during lateral stepping in response to external disturbances, the lateral instability of the head increases with age, the head righting decreases, and the head and trunk become one mass as the muscle activities increases to exert the neck lateral flexion moment, resulting in increased head acceleration. Our data suggest that the increased stiffness of the trunk and lower extremities due to vestibulospinal reflexes associated with increased head acceleration reduces the angular velocity of hip flexion and adduction of the step leg, leading to a decrease in the smoothness of the crossover step.

**Declarations**

**Acknowledgments**

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**Author contributions:**

Y.T. analyzed the data, interpreted the results, and wrote the manuscript. K.F. prepared the experimental setting. Y.T. and K.F. designed this study and performed all experiments. All Tables and Figures were made by Y.T.
Data availability statement:

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Additional information

Competing interests statement:

The authors declare no competing interests.

References


**Table**

**Table 1.** Amount of head swaying, righting angle, angular velocity, and lateral flexion neck moment during crossover steps.

<table>
<thead>
<tr>
<th></th>
<th>Head COM sway (m/s²)</th>
<th>Righting of the head</th>
<th>Lateral neck moment (Nm/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-P</td>
<td>M-L</td>
<td>S-I</td>
</tr>
<tr>
<td>Older</td>
<td>0.94±0.3</td>
<td>1.13±0.7</td>
<td>0.72±0.3</td>
</tr>
<tr>
<td>Young</td>
<td>0.92±0.5</td>
<td>0.54±0.3</td>
<td>0.74±0.3</td>
</tr>
</tbody>
</table>

A-P: anterior-posterior, M-L: medial-lateral, S-I: superior-inferior, COM: center of mass

*: p<0.05, **: p<0.01

**Figures**
Figure 1

Originally developed disturbance loader system.
Figure 2

Definition of head (a) and trunk (b) righting angles during a crossover step.
Figure 3

Relationship between neck moment and angular velocity of hip flexion during crossover steps (elderly group).
Figure 4

Relationship between neck moment and angular velocity of hip flexion during crossover steps (younger group).
Figure 5

Relationship between neck moment and angular velocity of hip adduction during crossover steps (elderly group).