Abstract. [Purpose] To describe the nature of multi-joint motor coordination during body rotation while in the standing position. [Participants and Methods] The participants were 22 healthy adults with no visual problems or history of diseases that could compromise their ability to execute body rotation. The position facing forward in an upright standing position was defined as 0°, and targets were placed at the following five points on concentric circles: 30°, 60°, 90°, 120°, and 150°. The participants always turned to the right. A three-dimensional motion analyzer consisting of six infrared cameras was used to measure the spatial coordinates of the infrared reflective markers. [Results] A main effect was found for all body segments. For all the target angles, the start of movement was approximately equal, and the angular change of the craniocervical joint was the largest. A nonlinear relationship was observed between the craniocervical and thoracolumbar joints for all target angles. However, a linear relationship was found between the thoracolumbar and pelvic joints. [Conclusion] The results of this study demonstrate that various regions such as the craniocervical and thoracolumbar junctions and the pelvis coordinate during such move to achieve optimal locomotive patterns. 

Key words: Motor coordination, Body rotation while standing, Multi-joint motor coordination

INTRODUCTION

Movements requiring multi-joint motor coordination, such as walking, standing, and turning, occur frequently in daily life. Efficient locomotion patterns are realized as a result of multi-joint motor coordination guided by the principle of conservation of energy cost in the execution of specific tasks, such as the forward reach, squat, and maintenance of a tandem stance. In the field of physical therapy, deviations from a normal manner established for each type of movement due to disease are used to estimate the degree of dysfunction; therefore, understanding motor coordination between adjacent joints is essential for clinical reasoning. Body rotation is often required for daily activities, and it is also used by physical therapists as a test to estimate dysfunction of the trunk or lower extremities. Fukuda et al. analyzed the body rotation of participants in a sitting position from the perspective of motor coordination and reported the detailed characteristics of various joint movements. However, body rotation can also be performed while in a standing position. Of these positions, lower limb joint movements are largely involved in the standing position. In addition, patterns of body rotation while in the standing position are affected by various constraining conditions such as balance, which requires increasingly complex and sophisticated motor coordination.
coordination of the adjacent joints. Despite this, our literature review did not yield any reports that involved the analysis of motor coordination over time with respect to body rotation while in the standing position. The purpose of this study was to describe the nature of multi-joint motor coordination during body rotation while in the standing position.

PARTICIPANTS AND METHODS

Participants were 22 healthy adults (11 men and 11 women; mean age, 21.3 ± 0.8 years; mean height, 166.5 ± 7.2 cm; mean body weight, 58.8 ± 8.3 kg) with no visual problems or history of diseases that could compromise their ability to execute body rotation. Consent was obtained from all participants after the nature and purpose of the present study and risk associated with the experiment was explained verbally and in writing. The study was approved by the Tohoku Bunka Gakuen University Research Ethics Committee (approval no. 15-16).

Body rotation in this study was defined as “directing the face toward the target object via rotational movement without altering the direction of the terminal part in contact with the floor.” Furthermore, target object recognition was achieved by eye movement and head orientation. The head orientation in this study was defined as “the sum of head and neck rotation, thoracolumbar rotation, and pelvic rotation (rotation of the hip joint and lower thigh and ankle inversion and eversion),” as shown in Equations 1 and 2 (Table 1).

Equation 1: Target=eye movement + head rotation (head orientation)
Equation 2: Head rotation (head orientation)=head and neck rotation + thoracolumbar rotation + pelvic rotation (hip rotation + lower thigh rotation + ankle inversion and eversion)

The position facing forward in an upright standing position was defined as 0°, and targets were placed at the following five points on concentric circles: 30°, 60°, 90°, 120°, and 150°. These were defined as the target angles. The target was a blue light-emitting diode (LED) light set at the height of the participant’s visual field. A buzzer was attached to the target object, which functioned as the starting signal. Furthermore, the center of the polar coordinates was established at the vertex, and the distances between the vertex and the target objects were set as 2 m. A three-dimensional motion analyzer (sampling frequency, 250 Hz; Locus 3D MA-5000; Anima Inc., Tokyo, Japan) consisting of six infrared cameras was used to measure the spatial coordinates of the infrared reflective markers (Fig. 1). Infrared reflective markers were attached at the following seven points on the participants’ bodies: the vertex, the auricle of both ears, the spinous process of the seventh cervical vertebra (C7 vertebra), the sternal manubrium, and the posterior superior iliac spine. Measurements were performed while the participant was standing with feet apart to vertically align the second metatarsal bone with the anterior superior iliac spine. The second metatarsal bone was positioned perpendicular to the frontal plane. Both feet were fixed during motion, and both upper limbs were left in a hanging position. Participants always turned to the right. Body rotations were performed at normal velocity. After practicing three times, participants started body rotation with the starting sound signal and simultaneous emission of the target blue LED light and buzzer sound from the same point. Participants were instructed to push the end signal switch in their hand at the moment when their line of sight met the target LED light. The signal produced by the switch was recorded along with the start signal using a data acquisition system (PowerLab; ADInstruments, Dunedin, New Zealand). The sampling rate was set at 1,000 Hz. Turning to the target points was performed once for each target (five targets) in an order selected randomly based on a table of random sampling numbers.

Coordinate data obtained from the three-dimensional motion analyzer were processed with a MATLAB original program (R2007B; MathWorks, Natick, MA, USA), and the angles and angular velocity of the joints were calculated. Coordinate data were obtained by calculating the moving average per 89 data points, and the spline function was used to standardize the movement time to find the mathematic mean of the data of all participants. The initiation of movement was defined as the moment when the head rotation angular velocity exceeded the threshold value, and the completion of movement was defined as the first moment from the initiation of movement when the head rotation angular velocity returned to 0. The threshold value was set as the mean ± 3 standard deviations (SD) from the initiation of the measurement to the signal. Rotational angles of each joint at the completion of motion were defined as the final rotational angles.

The significance of the difference in the target angles (five levels) was tested among the body segments using one-way ANOVA, and a post hoc test was performed using Tukey’s honestly significant difference test. All data were analyzed using SPSS version 22. The level of significance was p<0.05.

RESULTS

There were no significant differences in the final rotational angles between men and women. The final rotational angles of the eye and three joints when they arrived at the target angles are displayed in the Table 2. The main effect was found for all body segments (ocular movement, F (4,105)=3.68, p<0.01; craniocervical rotation, F (4,105)=29.17, p<0.01; thoracolumbar rotation, F (4,105)=41.16, p<0.01; pelvic rotation, F (4,105)=10.83, p<0.01). Changes in the body rotation for each joint movement over time are shown in Fig. 2. For all target angles, the angular change of the craniocervical joint was the largest. Furthermore, interactive motor coordination between adjacent joints from the initiation to completion of movement are displayed in Fig. 3. There was a nonlinear relationship between the craniocervical and thoracolumbar joints for all target angles; however, a linear relationship was found between the thoracolumbar and pelvic joints.
The final rotational angle for each joint to the target angle was smallest for the thoracolumbar joint. Based on this observation, we believe that body rotations in the standing position comprise rotations with craniocervical and pelvic predominance rather than thoracolumbar rotations. Fukuda et al.\textsuperscript{13} reported that body rotation in the sitting position consists largely of

**Table 1. Definitions of the base and transfer axes used to calculate eye and joint rotation angles**

| Angle                  | Base and transfer axes definitions                                                                 |
|------------------------|---------------------------------------------------------------------------------------------------|
| Craniocervical rotation| Base axis: Line between the sternal notch and CVII spinous process                                 |
|                        | Transfer axis: Line perpendicular to the line between the corners of the two ears                   |
| Thoracolumbar rotation | Base axis: Line perpendicular to the line between the 2 PSIS                                        |
|                        | Transfer axis: Line between the sternal notch and CVII spinous process                             |
| Pelvic rotation        | Base axis: Frontal plane                                                                            |
|                        | Transfer axis: Line perpendicular to the line between the 2 PSIS                                    |
| Ocular movement        | Angle resulting from subtracting the head rotation angle (sum of the craniocervical, thoracolumbar, and pelvic angles) from the target angle |

PSIS: posterior superior iliac spines.

**Table 2. Final rotation angles of the eye and joints**

| Target angles (degrees) | Ocular movement (degrees) | Craniocervical rotation (degrees) | Thoracolumbar rotation (degrees) | Pelvic rotation (degrees) |
|-------------------------|---------------------------|-----------------------------------|----------------------------------|---------------------------|
| 30                      | 8.2 ± 6.0                 | 11.2 ± 7.5                        | 0.6 ± 6.5                        | 10.1 ± 9.5                |
| 60                      | 14.1 ± 24.9               | 21.6 ± 13.5                       | 4.8 ± 7.6                        | 19.5 ± 18.4               |
| 90                      | 18.2 ± 11.3               | 33.4 ± 14.1\textsuperscript{**}   | 10.5 ± 7.0\textsuperscript{**}   | 27.9 ± 17.3\textsuperscript{**} |
| 120                     | 26.7 ± 27.0\textsuperscript{**} | 40.1 ± 18.1\textsuperscript{**} | 19.1 ± 10.3\textsuperscript{**} | 34.1 ± 19.1\textsuperscript{**} |
| 150                     | 23.7 ± 27.0\textsuperscript{***} | 51.7 ± 13.2\textsuperscript{**}, \textsuperscript{***}, \textsuperscript{,i} | 32.7 ± 11.5\textsuperscript{**,i,*,i} | 42.0 ± 22.0\textsuperscript{**}, \textsuperscript{***}, \textsuperscript{,i} |

\textsuperscript{a}Statistically significant difference between 30 degree and 90 degree.  
\textsuperscript{b}Statistically significant difference between 30 degree and 120 degree.  
\textsuperscript{c}Statistically significant difference between 30 degree and 150 degree.  
\textsuperscript{d}Statistically significant difference between 60 degree and 90 degree.  
\textsuperscript{e}Statistically significant difference between 60 degree and 120 degree.  
\textsuperscript{f}Statistically significant difference between 60 degree and 150 degree.  
\textsuperscript{g}Statistically significant difference between 90 degree and 120 degree.  
\textsuperscript{h}Statistically significant difference between 90 degree and 150 degree.  
\textsuperscript{i}Statistically significant difference between 120 degree and 150 degree.  
\textsuperscript{*}p<0.05, \textsuperscript{**}p<0.01.

**DISCUSSION**

The final rotational angle for each joint to the target angle was smallest for the thoracolumbar joint. Based on this observation, we believe that body rotations in the standing position comprise rotations with craniocervical and pelvic predominance rather than thoracolumbar rotations. Fukuda et al.\textsuperscript{13} reported that body rotation in the sitting position consists largely of
craniocervical and thoracolumbar rotations, and that rotation of the pelvis was insignificant. Due to the inhibition of pelvic rotation, the gluteal region serves as a support base during body rotation while in the sitting position. In contrast, body rotation while in a standing position allows for active use of pelvic rotational movement facilitated by high ranges of motion of the joints of the lower extremities, thereby decreasing the relative involvement of thoracolumbar rotation.

A closer look at angular changes demonstrated that the craniocervical angle exhibited the most extensive change, followed by the pelvis (Fig. 2). Interactive changes in angles of adjacent joints from the initiation and completion of motion also exhibited non-linear changes with respect to motor coordination between the craniocervical and thoracolumbar joints compared to the linear changes observed regarding motor coordination between the thoracolumbar joint and pelvis (Fig. 3). According to Fukuda et al.\textsuperscript{13}, craniocervical, thoracolumbar, and pelvic rotational movements initiate almost simultaneously during body rotation while in the sitting position. The craniocervical joint underwent the largest angular change, followed by the thoracolumbar joint. However, Fukuda et al. also reported that the relationships between motor coordination and the craniocervical and thoracolumbar joints and the thoracolumbar and pelvic joints were non-linear. Consistent with the report by Fukuda et al.\textsuperscript{13}, we also believe that the craniocervical joint underwent the largest angular changes while in the standing position, possibly as a motor strategy selected for minimizing energy costs\textsuperscript{1}. That is, tensile force generated by muscle moment is necessary for the initial body rotation. Rather than exhibiting the muscle moment in a body segment with heavier weight, it is exhibited in a lighter body segment because the energy cost is lower. As such, fine adjustments of the head position are also necessary when searching for the target using sensory capacities such as vision or hearing; direct control of the head position is more efficient. Therefore, with respect to the interactive angular changes of the head and thoracolumbar joints, the first half of the motion consists of predominantly craniocervical motions for the purpose of energy conservation.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Fig_2.png}
\caption{Changes in joint movements during body rotation over time.}
\end{figure}
whereas the latter half of the motion mainly consists of thoracolumbar motions for the purpose of making fine positional corrections to align with the target angle. This is likely why the relationship with motor coordination was non-linear.

In contrast, interactive angular changes occurring between the thoracolumbar joint and pelvis exhibited linear motor coordination with an even distribution of movements throughout the motion. Impingement of substantial inertial force on the body is likely to disrupt balance during rotation of the pelvis while in the standing position because the pelvis bears 70% of the total body weight\(^{14}\). Therefore, the optimal motion pattern selected under given balance constraints is likely to decrease the degree of freedom of motion and keep the center of gravity from oscillating as much as possible, thereby producing coordinated motion control between the thoracolumbar joint and pelvis.

The characteristics of body rotation while in the standing position are influenced by various constraints on physical movement, such as balance to maintain posture, and the anatomical and physiological characteristics of each joint. The results of this study demonstrated that various regions, such as the craniovertebral and thoracolumbar junctions and the pelvis, coordinate during such movements to achieve optimal locomotive patterns. These patterns manifest as highly efficient body rotation guided by the principle of conservation of energy.

**ACKNOWLEDGEMENT**

The authors gratefully acknowledge the assistance of the following individuals: Kota Sakurai, Rena Obata, Mizuki Endo, Shio Sato, Yo Nakajima, Mizuki Hayakawa, Ryosuke Mori, and Yumi Wakamatsu.

**Conflict of interest**

None.
REFERENCES

1) Fujisawa H, Suzuki H, Murakami K, et al.: The relationship between energy cost and the center of gravity trajectory during sit-to-stand motion. J Phys Ther Sci, 2015, 27: 3883–3886. [Medline] [CrossRef]

2) Fujisawa H, Suzuki H, Kawakami S, et al.: Postural optimization during functional reach while kneeling and standing. J Phys Ther Sci, 2016, 28: 2362–2368. [Medline] [CrossRef]

3) Fujisawa H, Suzuki H, Murakami K, et al.: The role of interaction torque and muscle torque in the control of downward squatting. J Phys Ther Sci, 2016, 28: 613–620. [Medline] [CrossRef]

4) Yamasaki H, Tagami Y, Fujisawa H, et al.: Interaction torque contributes to planar reaching at slow speed. Biomed Eng Online, 2008, 7: 27. [Medline] [CrossRef]

5) Fujisawa H, Takeda R, Yamasaki H, et al.: Contribution of interaction torque in sit-to-stand motion. J Soc Biomech, 2010, 34: 240–247 (in Japanese). [CrossRef]

6) Suzuki M, Miki C, Suzuki H, et al.: Postural control in tandem stance by young females and community-dwelling elderly females: examination of interlimb coordination of center of pressure (COP). Annu Rep Tohoku Sect Jpn Phys Ther Assoc, 2015, 27: 45–50 (in Japanese).

7) Suzuki M, Fujisawa H, Suzuki H, et al.: Frequency analysis of the center of pressure in tandem stance in community-dwelling elderly. J Phys Ther Sci, 2017, 29: 828–831. [Medline] [CrossRef]

8) Baird JL, Van Emmerik RE: Young and older adults use different strategies to perform a standing turning task. Clin Biomech (Bristol, Avon), 2009, 24: 826–832. [Medline] [CrossRef]

9) Scotto Di Cesare C, Anastasopoulos D, Bringoux L, et al.: Influence of postural constraints on eye and head latency during voluntary rotations. Vision Res, 2013, 78: 1–5. [Medline] [CrossRef]

10) Wada O, Tateuchi H, Ichihashi N: The correlation between movement of the center of mass and the kinematics of the spine, pelvis, and hip joints during body rotation. Gait Posture, 2014, 39: 60–64. [Medline] [CrossRef]

11) Sung PS, Lee KJ, Park WH: Coordination of trunk and pelvis in young and elderly individuals during axial trunk rotation. Gait Posture, 2012, 36: 330–331. [Medline] [CrossRef]

12) Sung PS: A kinematic analysis for shoulder and pelvis coordination during axial trunk rotation in subjects with and without recurrent low back pain. Gait Posture, 2014, 40: 493–498. [Medline] [CrossRef]

13) Fukuda M, Higuchi A, Tomisawa Y, et al.: The coordination between head and trunk during looking around in sitting position. Annu Rep Tohoku Sect Jpn Phys Ther Assoc, 2016, 28: 46–54 (in Japanese).

14) Winter DA: Biomechanics and motor control of human movement, 4th ed. New York: John Wiley & Sons, 1990.