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Comparison of lower limb joint moment and power during turning gait between young and old adults using hierarchical Bayesian inference

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ABSTRACT

Age-related differences in lower limb joint moment (JM), and joint power (JP) during turning remain unclear. The present study investigated age-related differences in lower limb JM and JP during turning between young adults (YAs) and old adults (OAs). We introduced the hierarchical Bayesian inference for comparing and identifying differences in JM, angular velocity(ω), and JP at each stance phase in the two age groups. This study included 16 healthy YAs and 16 healthy OAs (8 men and 8 women in each group). Participants performed 90° step turns to the right at a self-selected natural speed. On comparing the age groups, during 90° step turning, the OA group exhibited larger extention hip JM and JP to control (brake) the upper body in the sagittal plane, exhibited larger abductor moment in each lower limb joint for preventing the body from leaning in the frontal plane during the mid-stance phase, and exhibited larger hip JP and ω and smaller ankle JM in the transverse plane to rotate the body during the mid-stance phase. Our findings suggested that the overall reliance on the hip joint to control body motion in each anatomical plane during step turning is higher in the OA group than in the YA group. In addition, the hierarchical Bayesian inference is useful for comparing the time courses of JM, ω, and JP.

1. Introduction

Fall-related injuries are serious public health problems among old adults (OAs) aged 65 years or above. It has been estimated that one in three OAs fall at least once per year (Hausdorff et al., 2001). Fall-related injuries, such as hip fractures and head traumas, can deteriorate the mobility of OAs and hence reduce their independence (Ambrose et al., 2013; Stevens et al., 2006). The expenses related to fall-related injuries have increased with the increase in the size of the elderly population (Englander et al., 1996), and these costs in turn increase the total medical cost in the society (Stevens et al., 2006).

Lower limb joint moment (JM) and joint power (JP) play key roles in controlling the center of mass (COM) motion for stable gait, and their age-related changes have been investigated (Kerrigan et al., 1998; Liu and Lockhart, 2006, 2009). Liu and Lockhart (2009) compared JM during straight walking between young adults (YAs) and OAs. They found no significant age-related differences in ankle, knee, and hip JM between YAs and OAs. Liu and Lockhart (2006) also investigated the 3D JM during straight walking among three different age groups—YAs, middle-aged adults, and OAs, and they found that the evertor muscle moment at the ankle joint was lower in OAs than in YAs and middle-aged adults; however, the aging effect was not significant for other JMs. Kerrigan et al. (1998) reported that ankle JP at the late stance phase during straight walking was lower in OAs than in YAs, regardless of gait velocity. These studies revealed the fundamental differences in straight walking between YAs and OAs. However, in daily life, there are often irregular steps, such as turns and non-straight steps (Glaister et al., 2007), which increase the possibility of falls (Yamaguchi et al., 2012). Most research on falls among OAs has focused on steady state walking instead of these irregular steps. To the best of our knowledge, age-related differences in lower limb JM and JP during turning are unclear. We hypothesized that there are age-related differences in lower limb JM and JP between YAs and OAs during turning gait. The present study aimed to compare lower limb JM and JP during 90° turning between YAs and OAs.

Peak values of kinetic and kinematic time courses have often been used for group comparisons (Kerrigan et al., 1998; Savelberg et al., 2007; Yamazaki and Tanino, 2015). Additionally,

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kinetic and kinematic data at specific phases have been used for group comparisons (Liu and Lockhart, 2006). However, these methods do not provide a chance to identify detailed differences depending on the gait phase. Recently, a new statistical approach using Bayesian statistics has been applied to estimate between-group differences. This approach employs the probability of difference as an alternative to the classical methods of hypothesis significance testing using *p*-values such as *t*-testing (Benjamin et al., 2018; Quintana and Williams, 2018; Wasserstein and Lazar, 2016). Using a unique approach combining a state-space model and hierarchical Bayesian inference, we identified the probability of differences in lower limb JM and JP among the YA and OA groups depending on the gait phase. The state-space model is a statistical model that separately estimates the system noise and observation noise, which are two types of errors involved in the observed time series, by assuming potential variables that are not observed directly (Fukuya, 2016). Using the hierarchical Bayesian inference approach, we estimated the credible interval, which indicates the interval in which a parameter exists, and described the difference between two groups with a probability, which is difficult using the conventional multiple comparisons.

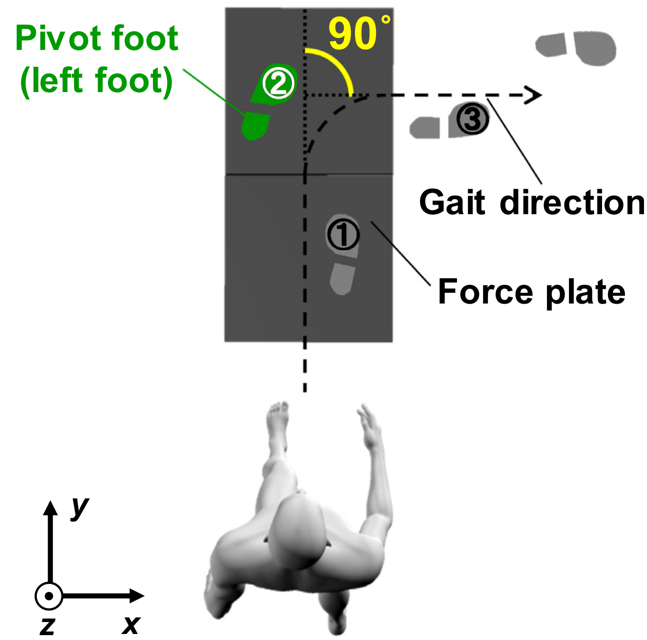

Fig. 1. Schematic footprints of 90° step turn to the right.

2. Methods

2.1. Participants

This study included 16 healthy YAs and 16 healthy OAs (eight men and eight women in each group). The age, height, and body mass of participants in the YA group were 21.6 ± 1.2 years (range, 20–23 years), 1.64 ± 0.08 m, and 59.5 ± 8.0 kg (mean ± standard deviation), respectively. The OA group data were collected in a previous study (Yamaguchi et al., 2018). The age, height, and body mass of participants in the OA group were 71.8 ± 4.5 years (range, 65–83 years), 1.58 ± 0.07 m, and 63.2 ± 11.6 kg, respectively. The participants exhibited no limitation owing to the neuromuscular, cognitive, and musculoskeletal disorders or injuries that may affect their balance/gait. The participants were informed of the protocol, and they provided written informed consent prior to the experiment. The protocol was approved by the Institutional Review Board of Tohoku University.

2.2. Experimental procedure

The experimental setup was as previously described (Yamaguchi et al., 2017, 2018). The data for the YA group were originally collected in the current study according to the protocol in a previous study (Yamaguchi et al., 2018). The length of the walkway was 5 m, and two force plates (MG-2060; Anima Corp., Tokyo, Japan) were installed approximately 3 m from the start position for collecting ground reaction forces (GRFs). Whole-body kinematics were measured with 16 infrared reflective markers placed bilaterally on all four extremities (including the shoulder, elbow, wrist, iliac crest, trochanter, knee, ankle, and metatarsus) using a motion-capture system equipped with eight cameras (MA8000, Anima Corp.). The sampling frequency for kinematics and kinetics data was 500 Hz. The same commercially available walking shoes (EASYSTAR2; Mizuno, Osaka, Japan) were used for each participant.

They were instructed to walk in a straight line and step on the first force plate with the right foot and then turn 90° to the right with the left foot (step turn, Fig. 1) on the second force plate. To indicate the turning direction, lines were marked on the floor. Sedgman et al. (1994) demonstrated that most turning angles during daily life activities are between 76° and 120°. Therefore, we instructed participants to perform a 90° step turn to the right at a self-selected natural speed. The difference in natural turning behavior among the YA and OA groups was demonstrated in the present study. The participants were allowed a practice period to become familiar with the step turning. The starting position (approximately 3 m from the first force plate) was adjusted so that the foot strike occurred on the force plate. After the practice period and position adjustment, each trial was replicated five times in each participant.

2.3. Data analysis

The GRF data (F_x, F_y, and F_z) of the second force plate for the pivot foot were collected, and the position of whole-body COM was estimated using a seven-segment model involving kinematic data with motion analysis software (MA8000). Fourth-order, zero-lag, Butterworth low-pass filtering with a 10-Hz cutoff frequency was performed on the GRF and kinematic data using this software. MATLAB (Mathworks, Natick, MA, USA) was used for subsequent analyses. The mean COM velocities during turning, representing the turning velocities, for the YA and OA groups were determined.

The JM values of each joint for *y-z* (JM_x), *z-x* (JM_y), and *x-y* (JM_z) were calculated with motion analysis software (MA8000) using the inverse dynamic method. The definitions of the global coordinates (*x*, *y*, and *z*) are shown in Fig. 1. The JP values of each joint for *y-z* (JP_x), *z-x* (JP_y), and *x-y* (JP_z) were calculated according to the products of JM and joint angular velocity ω (ω_x, ω_y, and ω_z), which was determined by the differential of the joint angle, as follows:

$$JP_x = JM_x \times \omega_x \quad (1)$$

$$JP_y = JM_y \times \omega_y \quad (2)$$

$$JP_z = JM_z \times \omega_z \quad (3)$$

The JM, ω, and JP data during the stance phase of the pivot foot were extracted and used for analysis. All data were normalized to 0–100% stance phase.

The local coordinate directions, i.e., mediolateral (ML: x' axis) and anteroposterior (AP: y' axis) directions, during turning were defined using the orientation of the pelvis to construct a body-fixed reference frame (Fino et al., 2015; Yamaguchi et al., 2017, 2018). As shown in Fig. 2, the x' axis originated parallel to the line through the mean position of the left iliac crest and left trochanter markers and the mean position of the right iliac crest and right trochanter markers. The y' axis was defined as the line perpendicular to the x' axis on the x–y plane. The sagittal plane (y'–z plane) and frontal plane (z-x' plane) components of lower limb JM, ω, and JP ($JM_{x'}$, $JM_{y'}$, $\omega_{x'}$, $\omega_{y'}$, $JP_{x'}$, and $JP_{y'}$) for each joint during the stance phase of the pivoting foot were calculated using the pelvis rotation angle α (Fig. 2) as follows:

$$\begin{bmatrix} JM_{x'} \\ JM_{y'} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} JM_x \\ JM_y \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \omega_{x'} \\ \omega_{y'} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} JP_{x'} \\ JP_{y'} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} JP_x \\ JP_y \end{bmatrix} \tag{6}$$

The JM and JP data were normalized by the mass of each participant.

2.4. Statistical analysis using hierarchical Bayesian inference

We created state-space models for lower limb JM, ω, and JP in the YA and OA groups using hierarchical Bayesian inference and calculated the probability of a difference between the two groups for each moment in the stance phase. Thereafter, we compared the output of this approach with that obtained from conventional multiple comparisons based on t-tests, such as the Benjamini & Hochberg (BH) method (Benjamini and Hochberg, 1995) and the Holm correction (Chan et al., 2007).

The hierarchical Bayesian inference was used to estimate the state-space model (time series data) of median values and the credible intervals of JM, ω, and JP in each anatomical plane for each joint. In hierarchical Bayesian inference, the posterior distributions of the JM, ω, and JP values were estimated by using the prior distributions and likelihood of the JM, ω, and JP values, respectively. The hierarchical Bayesian inference was performed using R (RStan, version 3.5.3, R Core Team). In this study, the below models for JM, ω, and JP values were assumed.

- The data in the YA group (x_{YA}) and OA group (x_{OA}), which corresponded with the calculated JM and JP, were obtained according to a normal distribution $[N(\mu[t], \sigma^2)]$, with individual differences and observation errors added to the baseline.
- The distributions of the data in the YA group and OA group have respective baselines (μ_{YA} and μ_{OA}), which corresponded with the estimated mean values, and their baseline random walk was determined according to the respective variance ($\sigma^2_{\mu YA}$ and $\sigma^2_{\mu OA}$).
- The difference (δ) between the YA group and OA group was determined with subtraction of their baseline data.

The model equations were set to create the above models as follows:

$$x_{YA}[n, t] \sim N(\mu_{YA}[t], \sigma^2_{YA}) \tag{7}$$

$$x_{OA}[n, t] \sim N(\mu_{OA}[t], \sigma^2_{OA}) \tag{8}$$

$$\mu_{YA}[t] \sim N\left(\mu_{YA}[t-1], \sigma^2_{\mu YA}\right) \tag{9}$$

$$\mu_{OA}[t] \sim N\left(\mu_{OA}[t-1], \sigma^2_{\mu OA}\right) \tag{10}$$

$$\delta[t] = \mu_{YA}[t] - \mu_{OA}[t] \tag{11}$$

where t is the percentage of the stance phase (0–100%) and n is the number of participants (1–16).

The Markov chain Monte Carlo (MCMC) method (Fukuya, 2016) was performed using RStan to estimate the parameters $\mu_{YA}[t]$, $\mu_{OA}[t]$, σ^2_{YA}, σ^2_{OA}, $\sigma^2_{\mu YA}$, and $\sigma^2_{\mu OA}$. The MCMC method is an approach that can determine the posterior distribution of the parameters of interest without computing the normalizing constant (Reis and Stedinger, 2005). In the MCMC method, Monte Carlo simulation

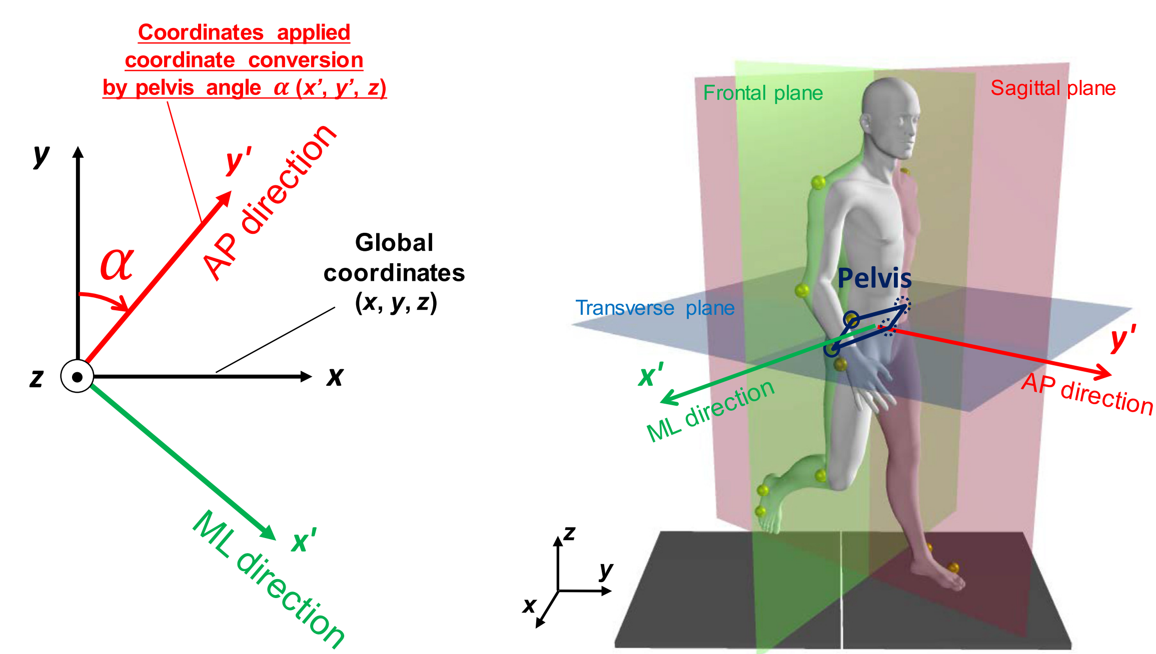

Fig. 2. Schematic diagram of the transverse pelvis rotation angle α and anatomical planes during turning.

was conducted with an approach that relied on the Markov property. The iteration number was set at 10,000, and the warmup number was 100 in the simulation. Random numbers were sampled every three times to reduce autocorrelation. Each estimation was replicated three times to confirm the accuracy of estimations. The probability of difference (P) values of JM, ω, and JP values between the YA and OA groups were calculated at each stance phase by using the credible interval of $\delta[t]$. The credible interval of $\delta[t]$ was calculated every 0.1%. The percentage of the widest credible interval not including 0 was defined as the probability of difference P between the two age groups.

Multiple comparisons using an independent t-test with Holm correction and the BH method were used to determine specific significant differences between the two age groups at each stance phase. A p-value < 0.05 was considered to indicate statistical significance.

3. Results

3.1. Turning velocity

The mean COM velocity for the YA and OA groups during turning were 1.00 ± 0.11 and 0.72 ± 0.12 m/s, respectively. The independent t-test indicated that the mean COM velocity of the OA group was significantly slower than that of the YA group ($p < 0.001$).

3.2. Lower limb JM

Fig. 3 shows the lower limb JM for each anatomical plane in the YA and OA groups and the probability of difference P in the two age groups during 90° step turning. As shown in Fig. 3A, there were differences in ankle JM with a probability of 99.9% during 10%, 13–15%, and 79% of the stance phase in the sagittal plane, 24% and 26–70% of the stance phase in the frontal plane, and 11% and 42–86% of the stance phase in the transverse plane. As shown in Fig. 3B, there were differences in knee JM with a probability of 99.9% during 44–77% of the stance phase in the sagittal plane, 39–71% of the stance phase in the frontal plane, and 53–57%, 59–61%, and 63% of the stance phase in the transverse plane. As shown in Fig. 3C, there were differences in hip JM with a probability of 99.9% during 11–99% of the stance phase in the sagittal plane, 37–67% of the stance phase in the frontal plane, and 70–91% of the stance phase in the transverse plane.

3.3. Lower limb joint angular velocity

Fig. 4 shows the lower limb joint angular velocity ω for each anatomical plane in both the YA and OA groups, along with the probability of difference P in the two age groups during a 90° step turn. As shown in Fig. 4A, differences in ankle joint ω were observed, with a corresponding probability of 99.9% during 1–15% and 84–89% of the stance phase in the sagittal plane, at

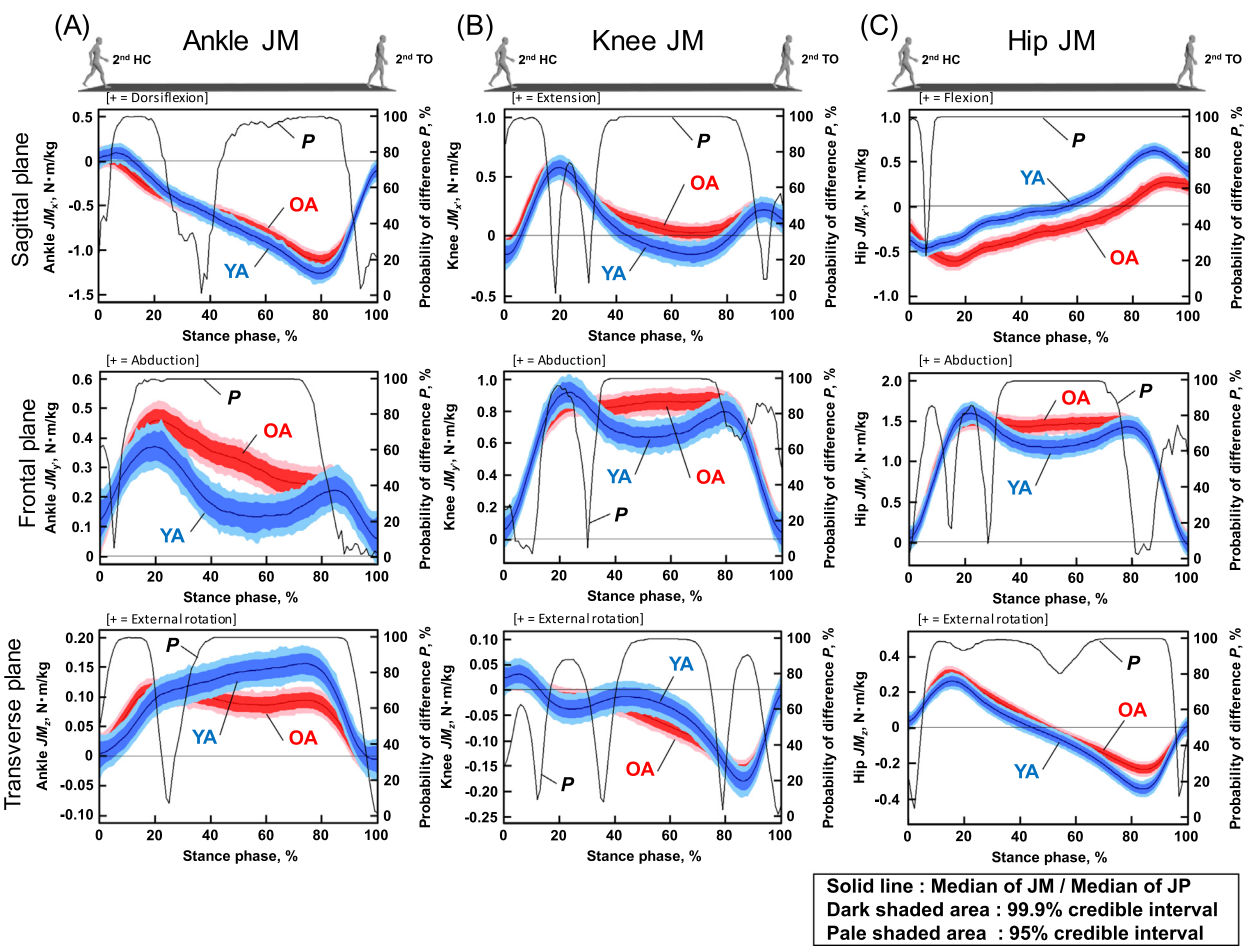

Fig. 3. Representative temporal changes in (A) ankle JM, (B) knee JM, and (C) hip JM with regard to sagittal, frontal, and transverse plane components. JM_x, JM_y, and JM_z are sagittal, frontal, and transverse plane components, respectively. The black, blue, and red solid lines indicate the probability of difference (P), the median JM value in the YA group, and the median JM value in the OA group, respectively. The dark and pale shaded areas indicate the 95% credible interval and 99.9% credible interval, respectively. JM, joint moment; YA, young adult; OA, old adult. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

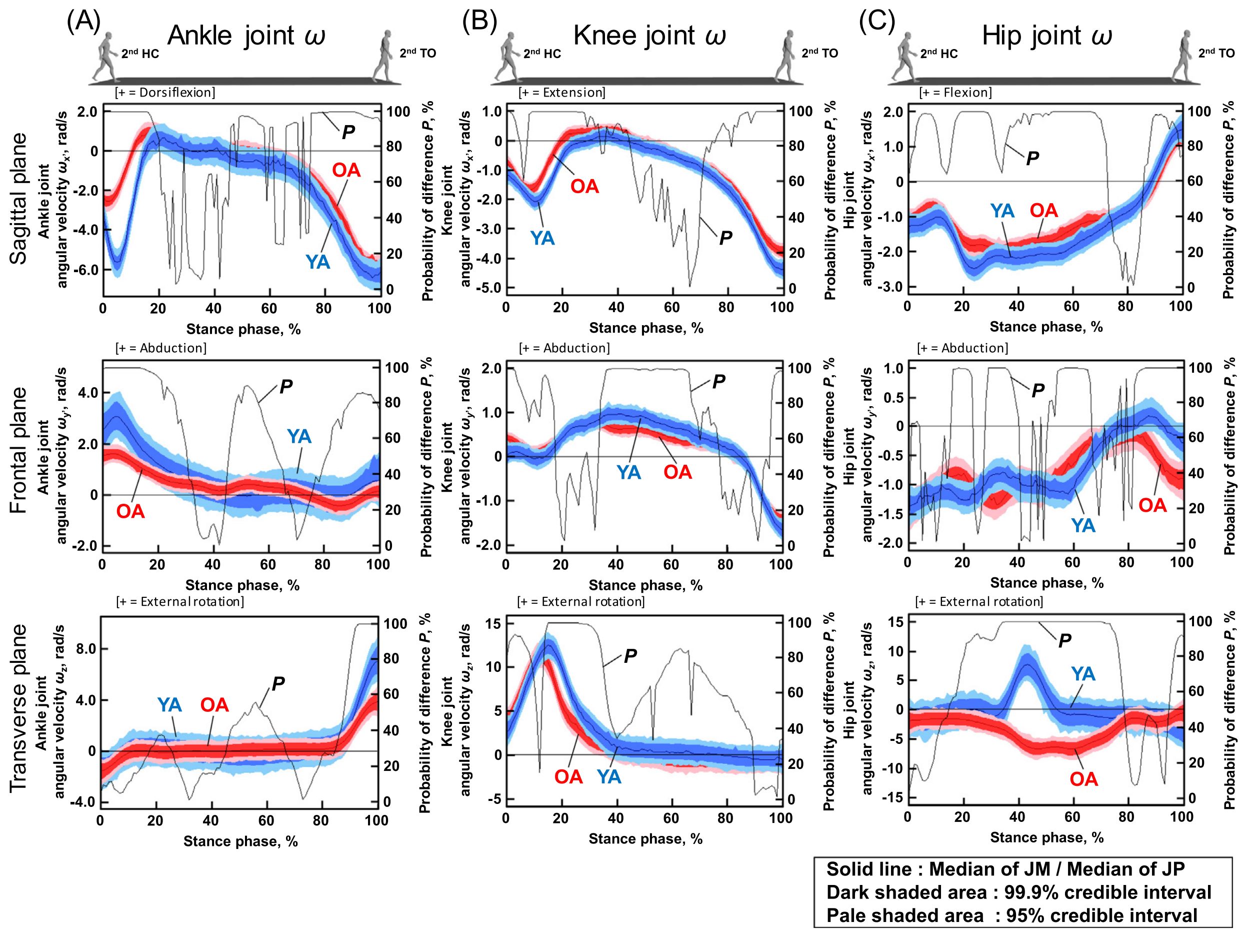

Fig. 4. Representative temporal changes in (A) ankle joint angular velocity (ω), (B) knee joint ω, and (C) hip joint ω with regard to the sagittal, frontal, and transverse plane components. ω_x, ω_y, and ω_z are the sagittal, frontal, and transverse plane components, respectively. The black, blue, and red solid lines indicate the probability of difference (P), the median ω value in the YA group, and the median ωvalue in the OA group, respectively. The dark and pale shaded areas indicate the 95% credible interval and 99.9% credible interval, respectively. YA, young adult; OA, old adult. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1–12% of the stance phase in the frontal plane, and at 94–100% of the stance phase in the transverse plane. Fig. 4B shows variations in knee joint ω with a corresponding probability of 99.9% at 10–24% and 91–100% of the stance phase in the sagittal plane, at 38–46%, 54–55%, and 57% of the stance phase in the frontal plane, and at 15–26% of the stance phase in the transverse plane. Similarly, Fig. 4C presents differences in hip joint ω with a calculated probability of 99.9% at 20–27% and 55–66% of the stance phase in the sagittal plane, at 18%, 30–34%, 60%, and 86–100% of the stance phase in the frontal plane, and at 35–70% of the stance phase in the transverse plane.

3.4. Lower limb JP

Fig. 5 shows the lower limb JP for each anatomical plane in the YA and OA groups and the probability of difference in the two age groups during 90° step turning. As shown in Fig. 5A, there were differences in ankle JP with a probability of 99.9% during 71–92% of the stance phase in the sagittal plane, 2–15% and 51–65% of the stance phase in the frontal plane, and 96–97% of the stance phase in the transverse plane. As shown in Fig. 5B, there were differences in knee JP with a probability of 99.9% during 2%, 4–5%, 7%, 14–25%, 75–78%, 81%, and 97–98% of the stance phase in the sagittal plane, and 14–17% and 24–28% stance phase in the transverse plane. As shown in Fig. 5C, there were differences in hip JP with a probability of 99.9% during 13–83% and 92–99% of the stance phase in the sagittal plane, 16–23%, 29–36%, and 87–91% of the stance phase in the frontal plane, and 45–51% and 65–82% of the stance phase in the transverse plane.

3.5. Comparison between hierarchical Bayesian inference and the conventional method

The results of multiple comparisons were compared with the results of hierarchical Bayesian inference. Fig. 6 shows the comparison between the results of hierarchical Bayesian inference and those of multiple comparisons for hip JM and JP in the sagittal plane. The independent t-test with Holm correction and the BH method (Fig. 6A) revealed that the hip JM in the sagittal plane was significantly different during 0% and 70–100% of the stance phase and 0–2% and 15–100% of the stance phase in both groups ($p < 0.05$). Additionally, the independent t-test with Holm correction and the BH method (Fig. 6B) revealed that the hip JP in the sagittal plane was significantly different during 71–80% of the stance phase and 32–45%, 61–84%, and 94–98% of the stance phase in both groups ($p < 0.05$).

4. Discussion

4.1. Sagittal plane

Our results revealed that age-related changes in JM in the sagittal plane mostly appear in the hip joint during almost the entire

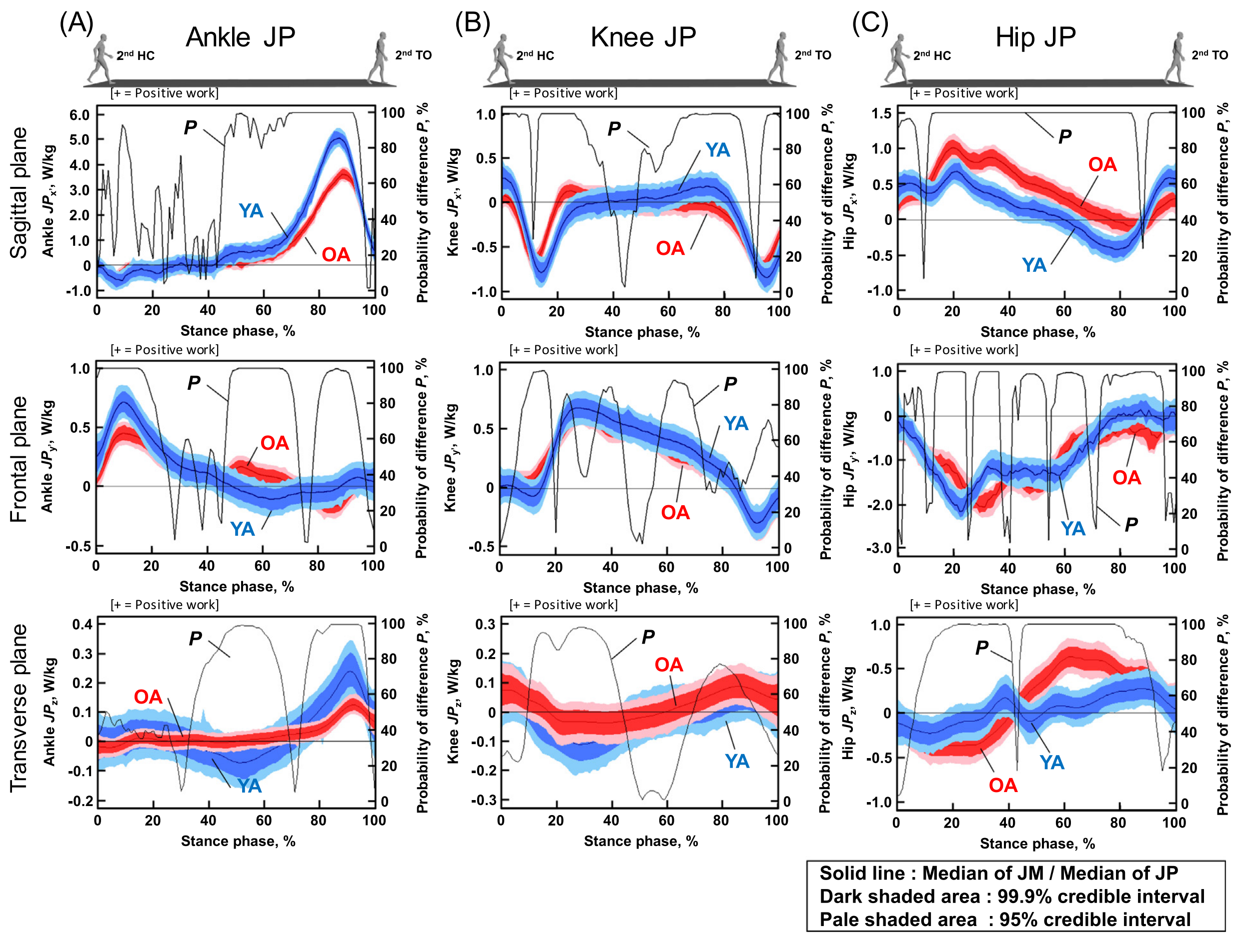

Fig. 5. Representative temporal changes in (A) ankle JP, (B) knee JP, and (C) hip JP with regard to the sagittal, frontal, and transverse plane components. JP_x, JP_y, and JP_z are the sagittal, frontal, and transverse plane components, respectively. The black, blue, and red solid lines indicate the probability of difference (*P*), the median JP value in the YA group, and the median JP value in the OA group, respectively. The dark and pale shaded areas indicate the 95% credible interval and 99.9% credible interval, respectively. JP, joint power; YA, young adult; OA, old adult. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

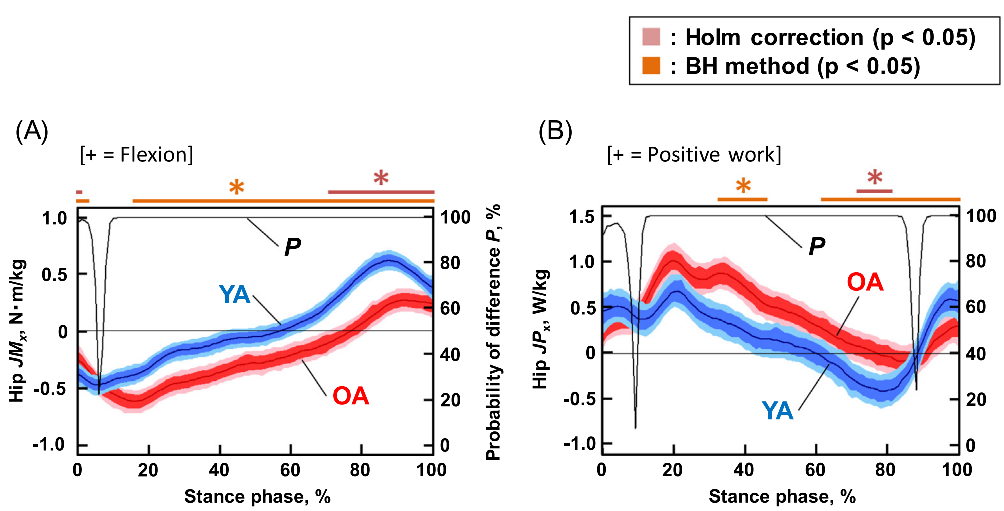

Fig. 6. Comparison of the results of hierarchical Bayesian inference and conventional multiple comparisons (Holm correction and BH method) for hip JM and JP in the sagittal plane. The dark red shaded area indicates a significant difference in each variable between the YA and OA groups with Holm correction. The orange shaded area indicates a significant difference in each variable between the YA and OA groups with the BH method. The significance level is 0.05. BH, Benjamini & Hochberg; JM, joint moment; JP, joint power; YA, young adult; OA, old adult. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stance phase, except in the early part of the phase. In addition, age-related changes in JP in the sagittal plane mostly appear in the ankle during the late stance phase, which is in agreement with the findings of a previous straight gait study (Kerrigan et al., 1998), and in the hip joint during almost the entire stance phase, except in the early and late parts of the phase. From these results, the OA group turned with a larger hip extension moment and positive hip JP for a longer period when compared with the findings in the YA group. Hip extension JM in the sagittal plane contributes to controlling the forward rotation of the upper body (Winter, 2009). Therefore, the OA group controlled (prevented) the forward rotation of the upper body with a large and long hip extension moment. The increased extension hip JP observed in the OA group might be due to the weakened iliopsoas muscle associated with aging (Kuno et al., 2003). The JP associated with the extensor muscle group in the OA group could become relatively large owing to the weakened flexion muscle group of the iliopsoas muscle. Our results also indicate that the OA group turned with a small hip flexion moment and small hip JP for a shorter period when compared with the findings in the YA group in the late stance phase. As the OA group had a small hip flexion JM in the sagittal plane, which is used for lifting the pivot foot up (Winter, 2009), the ability to lift the thigh of the pivot foot forward and upward in this group deteriorated in the late stance phase of turning gait, which might reduce foot clearance and result in tripping (Winter, 1992).

In the present study, gait speed was not controlled in the adopted tasks. Several studies in the past (Chen et al., 1997; Fukuchi et al., 2019; Goldberg and Standhope, 2013) have demonstrated that during straight walking, both lower limb JM (both extension and flexion moments) and JP in the sagittal plane increase with the increase in walking speed. Our results indicated that turning speed was slower in the OA group than in the YA group. As shown in JM and JP data for the sagittal plane (Figs. 3 and 5, respectively), peak ankle planter flexion and dorsiflexion JM, hip flexion JM, and the corresponding JP values in the YA group were greater than those in the OA group, which is attributed to the age-related differences in turning speed. However, hip extension JM and corresponding JP values in the OA group were greater than those in the YA group. These observations contradict conventional findings in terms of the effect of walking speed on hip JM and JP and can be attributed to age-related changes in turning gait strategy and muscle function(s) during turning.

4.2. Frontal plane

Age-related changes in ankle, knee, and hip JM in the frontal plane mostly appear during the mid-stance phase. However, there were no remarkable age-related differences in JP in the frontal plane. From these results, the angular velocity ω of each joint might be smaller in OAs than in YAs during the mid-stance phase because of slower turning speed (Yamaguchi et al., 2018). Yamaguchi et al. (2018) indicated that the body lean angle during turning was smaller in OAs than in YAs in the entire stance phase. Therefore, in conjunction with these results, the OA group turned with a large abductor moment in each joint during the mid-stance phase to prevent the body from leaning in the medial direction. On the other hand, the YA group might lean the body during the mid-stance phase using the gravity acting on the COM.

4.3. Transverse plane

The ankle JM in the transverse plane was lower in the OA group than in the YA group from the mid-stance to late stance phase. The hip JM in the transverse plane during the late stance phase was lower in the OA group than in the YA group. These results indicate that the YA group turned with larger twisting moment in the ankle and hip joint when compared with the finding in the OA group. On the other hand, the hip JP in this plane during the mid-stance phase was larger in the OA group than in the YA group, indicating that the angular (twisting) velocity ω of the hip joint in the transverse plane during this period was larger in the OA group than in the YA group. Additionally, this finding indicates that body rotation during this period in the stance phase was greater in the OA group than in the YA group, which was supported by the results of the difference in the hip joint ω between the two age groups, as shown in Fig. 4(C). These results suggest that the contribution of the hip joint to body rotation in the transverse plane during step turning is greater in the OA group than in the YA group, and the OA group turned with a smal body lean angle in the frontal plane. Because the body lean angle (COM-center of pressure inclination angle) is considered a measure of gait instability in OAs (Lee and Chou, 2006), turning with a small body lean angle may be effective in maintaining balance during turning in OAs. This adaptation may represent a major strategic difference in turning between the YAs and OAs that helps maintain balance and prevent a fall during turning.

4.4. Hierarchical Bayesian inference

The results indicated that hierarchical Bayesian inference is more sensitive than conventional multiple comparisons for indicating age differences in the hip joint in the sagittal plane (Fig. 6). The same trend was observed in the knee and ankle joint in the frontal and transverse planes, respectively. This is accompanied with the nature of Bayesian inference. The Bayesian inference approach estimates the posterior distribution of parameters from the prior distribution of the parameters and the likelihood of the data. In other words, the history of previous time information affects the estimation. Conversely, conventional multiple comparisons do not consider any previous time information.

5. Conclusion

In conclusion, on comparing the OA and YA groups during 90° step turning, the OA group exhibited greater extension hip JM and JP values for controlling the upper body in the sagittal plane, exhibited larger abductor moment in each lower limb joint for preventing the body from leaning in the frontal plane during the mid-stance phase, thereby resulting in a smaller body lean angle, and exhibited greater hip JP and smaller ankle JM values in the transverse plane for rotating the body from the mid-stance to late stance phase. Our findings suggest that reliance on the hip joint to control body motion in each anatomical plane during step turning is greater in the OA group than in the YA group. Our findings can be used as the basis for developing assistance and training strategies that help achieve an efficient gait in OAs. The results described here have considerable clinical applicability and provide insights into mechanical detriments that hinder performance. Therefore, these results can be used to design interventions for overcoming these issues, such as a walking assist device, which will help improve mobility in OAs. Additionally, we demonstrated the efficacy of using hierarchical Bayesian inference in comparison of the time courses of JM and JP. Further research is needed to investigate whether our results are applicable to elderly people with impaired health and mobility.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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