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Position and velocity controls in children and adults during a wrist tracking task

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Children's motor control skills develop with age, but it is unclear when the development begins and ends. To identify those critical points, we conducted a wrist tracking task and examined position and velocity controls in children and adults. The task consisted of a visible circular orbit, a target rotating at a constant speed of 0.1 Hz, a tracer reflecting the real-time position of the wrist joint, and target-visible and -invisible subsections. We had three age groups for younger children ($n = 16$, 8.00 ± 0.82 years old, Group 1), older children ($n = 13$, 11.62 ± 0.65 years old, Group 2), and adults ($n = 10$, 23.50 ± 2.88 years old, Group 3). Absolute angular position difference $\Delta\vartheta$ and absolute angular velocity difference $\Delta\omega$ between the target and tracer were computed to analyze the position and velocity control abilities. Statistical hypothesis tests on the control parameters revealed that the mean $\Delta\vartheta$ of Group 2 (4.06 ± 0.71 deg) was statistically smaller than Group 1 (6.17 ± 1.51 deg, $p = 0.006$) and equivalent to Group 3 (2.76 ± 0.51 deg, $p = 0.074$), whereas the mean $\Delta\omega$ of Group 2 (19.82 ± 4.50 deg/s) was statistically similar to Group 1 (20.46 ± 2.88 deg/s, $p = 0.999$) but greater than Group 3 (12.85 ± 2.03 deg/s, $p = 0.001$). It indicated that the preteen children between 10 and 12 years old performed accurate position controls like the adults and yet exercised immature velocity controls. However, we noticed that velocity controls in the older children were actively developing since they managed to decrease $\Delta\omega$ significantly during the target-invisible phase (17.44 ± 3.53 deg/s, $p = 0.002$), just like the adults did (11.77 ± 1.08 deg/s, $p = 0.017$). Therefore, we could also infer that preteen children between 10 and 12 are beginning to obtain feedforward abilities and internal models for the wrist tracking task.

The feedback mechanism, summarized as 'recognizing errors and revising actions,' provides the simplest explanation for the vital phenomena of various creatures. However, it alone cannot explain accuracy and smoothness in humans during fast movements because the delay time of our visuomotor coordination is about 0.15 s[1,2]. Therefore, scholars were convinced that a person also possesses the feedforward mechanism and internal models that inversely calculate the ideal motor command for the desired movement to compensate for the considerable delay. In simulations, the combination of feedback and feedforward controllers generated more stable responses, and the feedback-error-learning algorithms employed to the feedforward improved performance by iterations as humans do[3,4]. Then, researchers have confirmed that humans do have the feedforward and learning abilities in the brain[5–7]. fMRI studies provided direct evidence for internal models by discovering active blood flow in the brain during motor learning[8,9]. Studies on movement tasks reported that brain diseases affect control performance and deteriorate internal models[10–12]. As the relationship between the brain and predictive control has been revealed, the hypothesis that children obtain more accurate feedforward abilities and internal models as they grow has become convincing because the human brain continues to develop even in one's twenties[13–15].

Researchers have commonly testified that children's control abilities develop gradually with age. Mounoud et al. 1985 and Zanone 1990 were the earliest to examine motor controls in children under 9 and 15 years by conducting elbow-tracking tasks[16,17]. They pointed out that older children produced smaller position and velocity errors than younger children, but the magnitudes were not comparable to those of adults. Many studies followed to describe children's motor characteristics in other work environments like eye or digital-pen tracking and reported similar outcomes regarding their position and velocity controls[18–20]. Compiling the references, we have reached an interesting conclusion that children's abilities to control position are achieved before their abilities to control velocity. Hence, we wanted to identify when their development begins and ends, for the

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reference studies give only a vague clue that age 10 is the critical point for the change in control strategies. Since the development of speed discrimination skills is also notable around age 11[21], we could hypothesize that children start to obtain feedforward abilities and internal models in preteens between 10 and 12 years.

In our previous study, we conducted a wrist tracking task and observed the effect of visibility condition of a target moving in circles on motor control performance in adults[22]. We observed a significant increase in absolute angular position error and a notable decrease in angular velocity error as the visible target disappeared. It implied that the subjects changed their strategies from position-centered to velocity-centered controls. Consequently, we could infer that the subjects had feedforward abilities and internal models to recognize the target velocity during the visible phase and to reproduce it during the invisible phase. Because the wrist tracking task is simple enough to be performed by children, we have conducted this study to compare position and velocity controls in children and adults using the same apparatus. Although the motor control characteristics are limited to wrist rotations, we expected that this single joint movement would suggest more direct results about how human feedback and feedforward abilities develop with age.

Methods
Participants
Sixteen younger children (8.00 ± 0.82 years old, Group 1), thirteen older children (11.62 ± 0.65 years old, Group 2), and ten adults (23.50 ± 2.88 years old, Group 3) participated in this study. Since the experimental task involved wrist rotations, we recruited only right-handed subjects to keep the movement task consistent. The sample size was computed before the recruitment using G*Power (Heinrich-Heine-Universität Düsseldorf, Germany). Given the three subject groups, the repeated-measures ANOVA for within-between interaction required at least 36 samples, assuming the conventional statistical power ($1-\beta = 0.80$) and the large effect size ($f = 0.40$). Subject information such as intelligence quotient or coordinated motor skills was not collected, and we report this as a limitation of the study. The research was approved by the ethics committees of Handong Global University (2022-HGUA020) and conducted under the ethical standards of the Declaration of Helsinki. All subjects were fully informed about the research and provided written informed consent before the experiment.

Experimental setup
As shown in Fig. 1, each subject sat in a chair about 60 cm away from the computer monitor and grabbed a two-degree-of-freedom manipulandum with one's right hand while the forearm was comfortably supported on the armrest. The subject could freely rotate the wrist, and the device collected wrist flexion/extension and ulnar/radial deviation angles at a sampling rate of 1 kHz. The current wrist position was presented as a red closed circle (tracer) with a diameter of 1.0 cm on the monitor in real time. The conversion ratio from the rotational to the planar motions was 14.5 degrees to 8.4 cm. Hence, 1 degree in each flexion/extension or ulnar/radial deviation was equivalent to 0.579 cm in horizontal (X) or vertical (Y) motion, respectively. The apparatus was identical to our previous study[22].

Wrist tracking task
As shown in Fig. 2A, each subject was asked to perform a wrist tracking task. A black open circle (target) with a diameter of 1 cm was presented at the right end of a visible circular orbit with a radius of 8.4 cm, and the subject initially located the tracer on the stationary target. After 5 s, the target started to rotate counterclockwise along the orbit at a constant speed of 0.1 Hz (a tangential speed of 5.278 cm/s) for 40 s. The subject followed the target as closely as possible to match the position and velocity of the tracer to those of the target by actively rotating one's wrist.

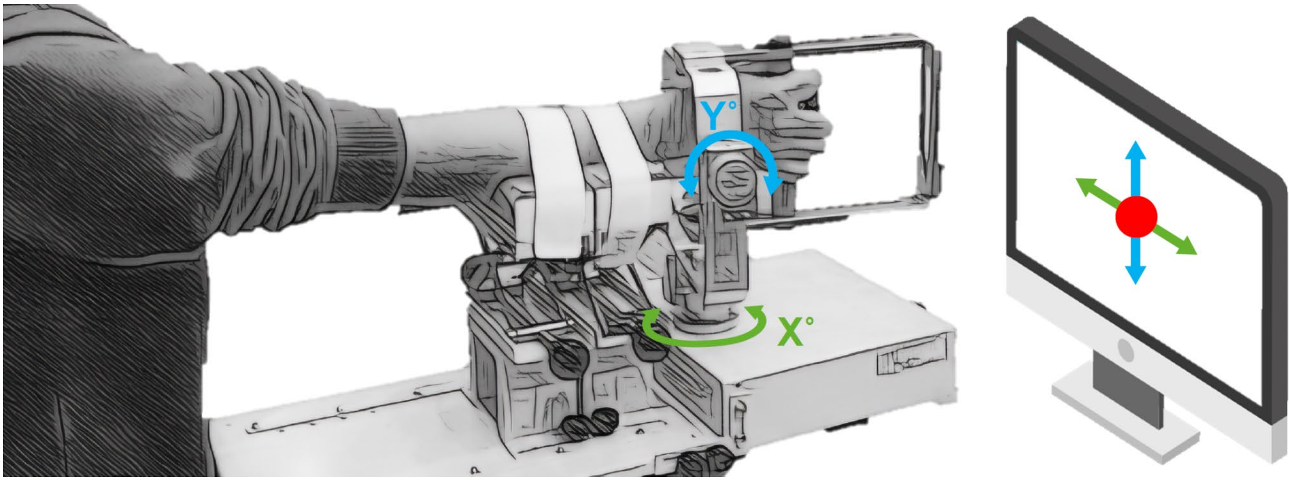

Fig. 1. Experimental setup. The wrist flexion/extension (angle X) and ulnar/radial deviations (angle Y) were measured by the manipulandum. The current joint position was depicted on the computer monitor as the red closed circle (tracer) with a conversion ratio of 14.5 degrees to 8.4 centimeters.

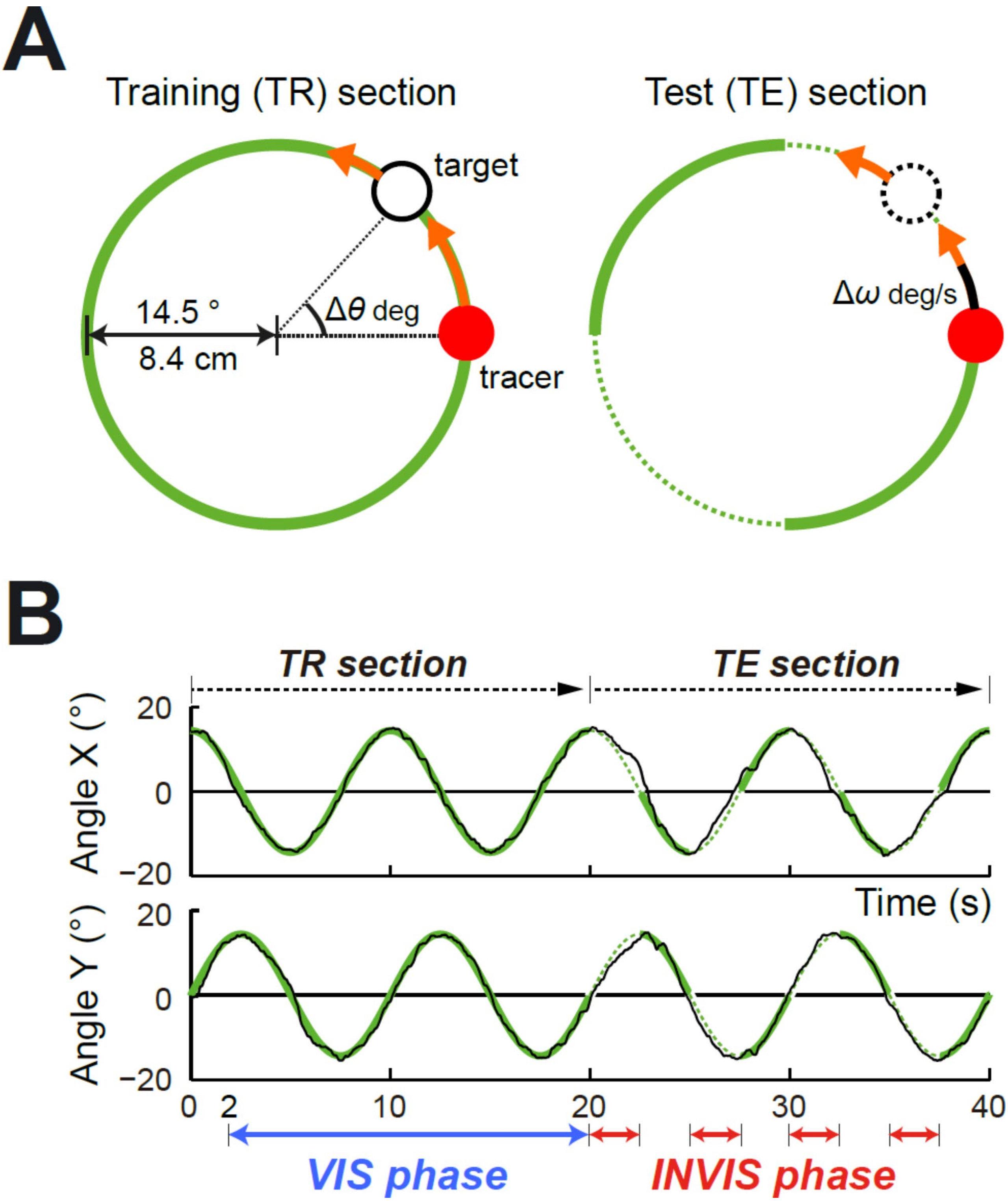

Fig. 2. Wrist tracking task. (A) The black open circle (target) rotates counterclockwise at 0.1 Hz. The task consists of the training (TR) and test (TE) sections. (B) The target-visible region in the TR section is labeled as VIS phase, and the target-invisible regions in the first and third quadrants in the TE section is labeled as INVIS phase.

The tracking task consisted of a training (TR) section and a test (TE) section, as shown in Fig. 2A and B. The first half was the target-visible TR section. Hence, the subject could directly observe the moving target and its current states to execute feedback control. The remaining half was the TE section, where the second and fourth quadrants of the orbit were still target-visible regions, but the first and third quadrants were target-invisible regions. Therefore, the subject should predict the state variables of the target to continue the tracking task. Each subject had more than 3 practice trials to adapt to the experiment and completed 3 main trials.

Data processing

The raw X and Y data collected by the device was processed by a 3rd -order low-pass Butterworth filter with a cutoff frequency of 6 Hz to remove measurement noise. The filtered data in the Cartesian coordinate system was then transformed into the polar coordinate system to compute angular displacement θ, and angular velocity ω. The symbol $\Delta\theta$ in Eq. (1) denotes the absolute difference in the angular displacement between the target and the tracer.

$$\Delta\theta\,[deg] = abs\left(\theta_{\,tracer}\,(t) - \theta_{\,target}\,(t)\right) \tag{1}$$

$$\Delta\omega\,[deg/s] = abs\left(\omega_{\,tracer}\,(t) - \omega_{\,target}\,(t)\right) \tag{2}$$

The symbol $\Delta\omega$ in Eq. (2) represents the absolute difference in the angular velocity between the target and the tracer.

The two parameters $\Delta\theta$ and $\Delta\omega$ were used to evaluate the position and velocity control accuracy during the tracking task. In the TR section, the interval from 2 to 20 s is labeled as the visible (VIS) phase shown in Fig. 2B because the subjects made sudden reactions to approach the target for the first 2 s. Hence, data in the VIS phase is used to analyze stable feedback responses with the visible target. In the TE section, the target-invisible first and third quadrants are labeled as the invisible (INVIS) phase. Thus, data in the INVIS phase is used to analyze predictive responses with the invisible target.

The entire data processing was performed using MATLAB (The MathWorks Inc., Natick, Massachusetts, USA). Kruskal-Wallis, Dunn-Bonferroni, and Wilcoxon signed-rank tests on $\Delta\theta$ and $\Delta\omega$ were conducted using IBM SPSS Statistics (IBM Corp., Armonk, New York, USA) to examine statistical differences among the age groups and between the two phases. Since the Shapiro-Wilk's test of normality revealed that some data are not normally distributed such as $\Delta\theta$ INVIS in G3 ($p = 0.043$) and $\Delta\omega$ INVIS in G1 ($p = 0.024$), we decided to conduct non-parametric tests rather than the previously assumed repeated-measures ANOVA to be more conservative and robust on the statistical significance. Effect sizes and statistical powers were estimated using G*Power[23–25].

Results

Figures 3 and 4, and 5 show typical movement characteristics of the younger children (Group 1), older children (Group 2), and adults (Group 3), respectively. Figures 3A and 4A, and 5A illustrate movement trajectories in the Cartesian coordinate system. It is notable that the adult and older child demonstrate smoother circles, while the younger child exhibits noticeably bumpy traces. Figures 3B and 4B, and 5B illustrate the angular position θ and its absolute difference $\Delta\theta$ of the representatives. $\Delta\theta$ signals and their means indicate that the adult subject has shown better position control followed by the older and younger children regardless of the visibility condition. Figures 3C and 4C, and 5C illustrate the angular velocity ω and its absolute difference $\Delta\omega$ of the subjects. $\Delta\omega$ signals and their means imply that the adult subject again has shown better velocity control in both the VIS and INVIS phases. $\Delta\omega$ of the older child is greater than that of the adult but smaller than that of the younger child.

Statistical hypothesis tests on Δθ

Figure 6 summarizes the statistical tests on $\Delta\theta$ according to the three age groups (a between-subject factor) and the visibility condition of the target (a within-subject factor).

Figure 6A shows the difference in $\Delta\theta$ among Groups in the VIS phase. The means and standard deviations are 6.17 ± 1.51 deg for Group 1, 4.06 ± 0.71 deg for Group 2, and 2.76 ± 0.51 deg for Group 3. The Kruskal-Wallis test in Table 1 reports that Groups have statistically different means in the VIS phase ($p = 8.05 \times 10^{-7}$). The Bonferroni-corrected Dunn's tests for post-hoc multiple comparisons in Table 2 reveal that Group 1 has significantly greater $\Delta\theta$ than Groups 2 and 3 ($p = 0.006$ between Groups 1 and 2; $p = 5.98 \times 10^{-7}$ between Groups 1 and 3). However, $\Delta\theta$ of Group 2 was not statistically different from that of Group 3 ($p = 0.074$ between Groups 2 and 3). It indicates that the position feedback control ability grows with age and almost reaches an adult level in preteens.

Figure 6B illustrates the difference in $\Delta\theta$ among Groups in the INVIS phase. The means and standard deviations are 10.30 ± 2.78 deg for Group 1, 6.72 ± 2.65 deg for Group 2, and 4.77 ± 1.23 deg for Group 3. The Kruskal-Wallis test in Table 1 reports that Groups have statistically different means in the INVIS phase ($p = 2.66 \times 10^{-5}$). The Bonferroni-corrected Dunn's tests for post-hoc multiple comparisons in Table 2 reveal that Group 1 again has significantly greater $\Delta\theta$ than Groups 2 and 3 ($p = 0.010$ between Groups 1 and 2; $p = 2.79 \times 10^{-5}$ between Groups 1 and 3). However, $\Delta\theta$ of Group 2 was not statistically different from that of Group 3 ($p = 0.296$ between Groups 2 and 3). These results indicate that the position predictive control ability also grows with age and nearly reaches an adult level in preteens.

Figure 6C and D, and 6E present the difference in $\Delta\theta$ regarding the visibility condition of the target within each Group. The Wilcoxon signed-rank tests in Table 3 suggest that $\Delta\theta$ in the INVIS phase are significantly greater than $\Delta\theta$ in the VIS phase regardless of Groups ($p = 4.38 \times 10^{-4}$ within Group 1; $p = 0.001$ within Group 2; $p = 0.005$ within Group 3). The increase was approximately 1.7 times in all Groups. These outcomes imply that the visibility of the target has a significant effect on the position control accuracy. The results validate the experimental design because it proves that the younger children in Group 1 had sufficient abilities to perform the tracking task more accurately during the VIS phase.

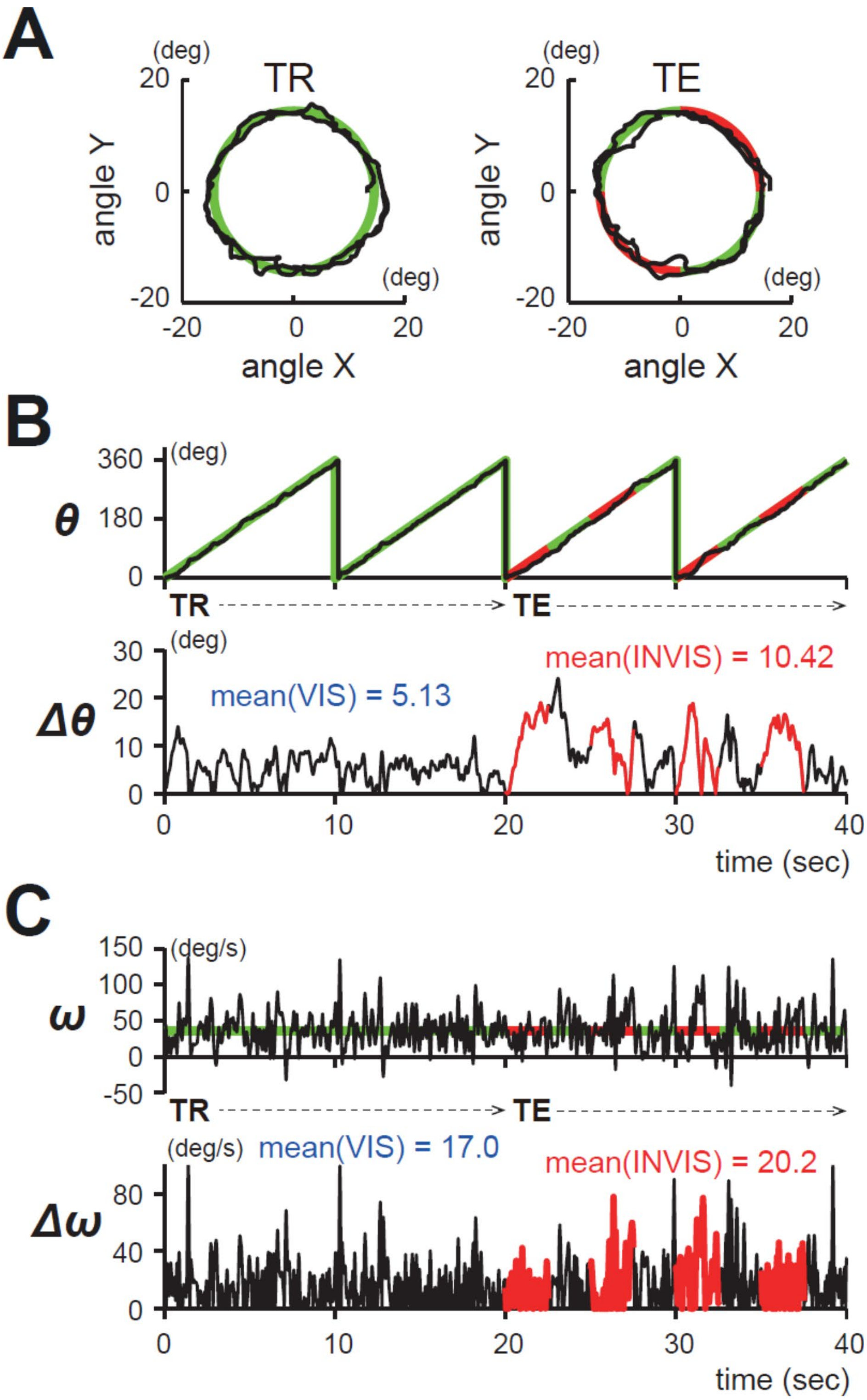

Fig. 3. Typical movement characteristics in Group 1. (A) Wrist X and Y positions during the TR and TE sections. (B) θ is the angular displacement of the tracer and $\Delta\theta$ its absolute difference from the target. (C) ω is the angular velocity of the tracer and $\Delta\omega$ its absolute difference from the target. As the target disappeared, both $\Delta\theta$ and $\Delta\omega$ were increased.

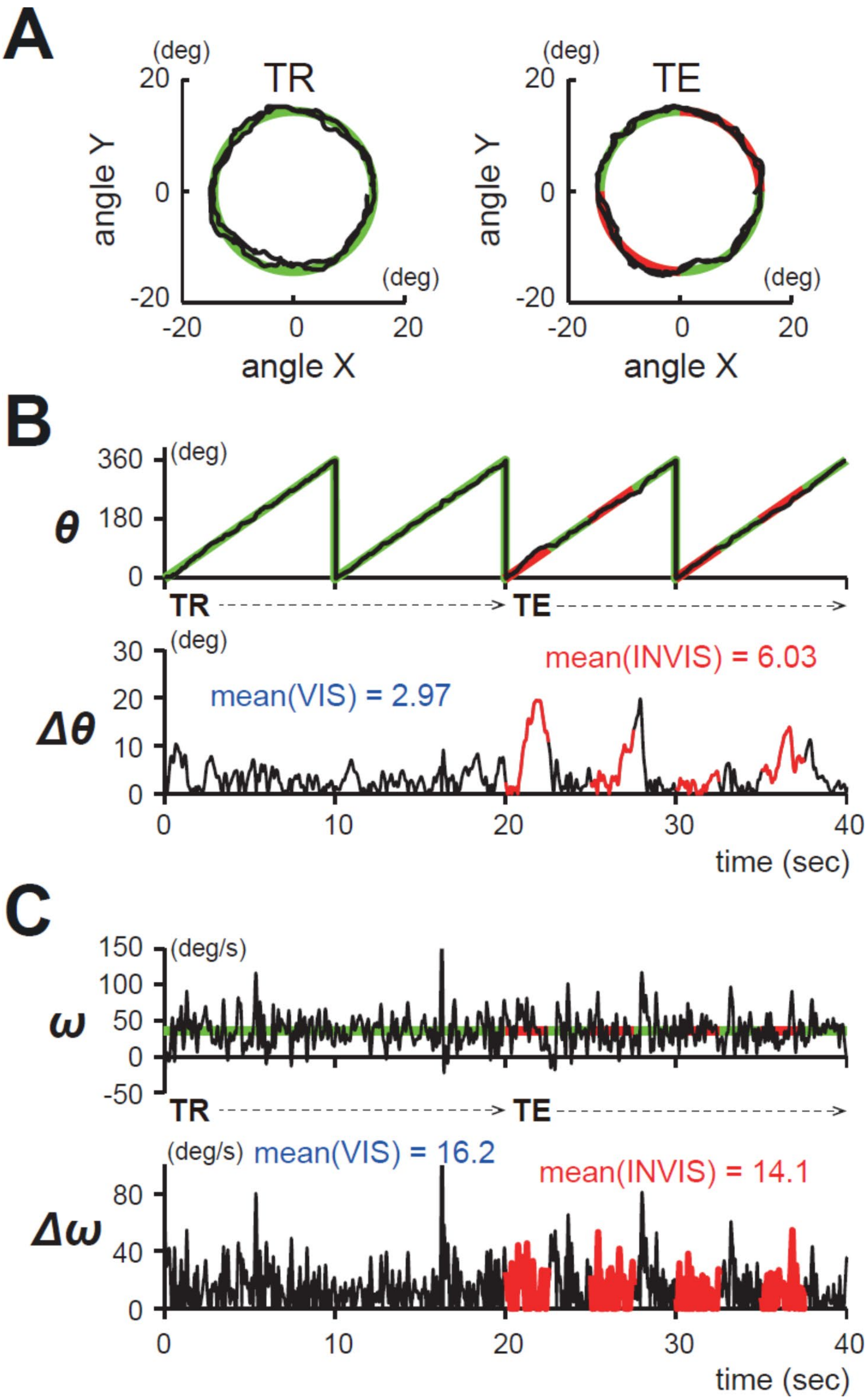

Fig. 4. Typical movement characteristics in Group 2. (A) Wrist X and Y positions during the TR and TE sections. (B) θ is the angular displacement of the tracer and $\Delta\theta$ its absolute difference from the target. (C) ω is the angular velocity of the tracer and $\Delta\omega$ its absolute difference from the target. As the target disappeared, $\Delta\theta$ was increased but $\Delta\omega$ was decreased.

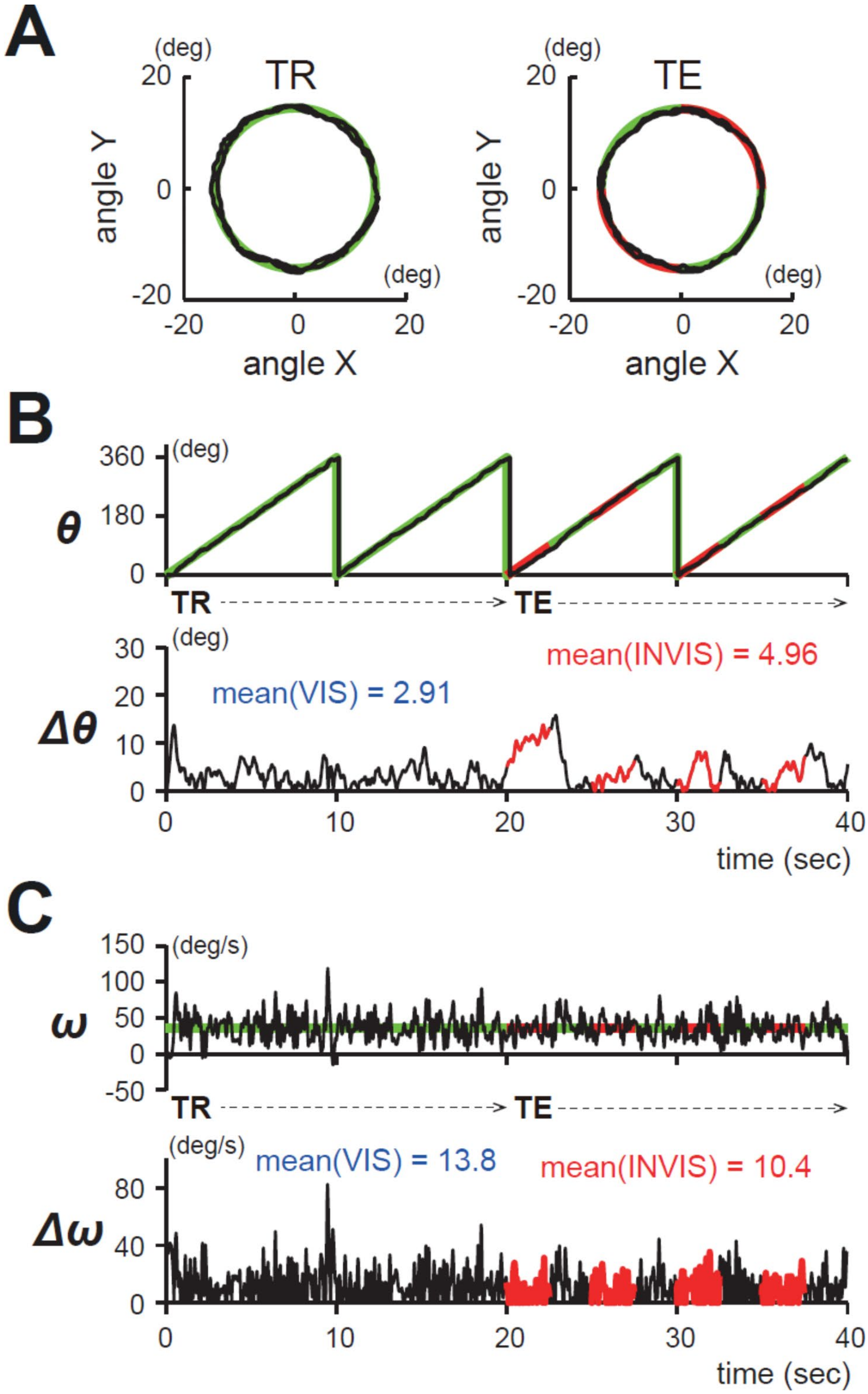

Fig. 5. Typical movement characteristics in Group 3. (A) Wrist X and Y positions during the TR and TE sections. (B) θ is the angular displacement of the tracer and $\Delta\theta$ its absolute difference from the target. (C) ω is the angular velocity of the tracer and $\Delta\omega$ its absolute difference from the target. As the target disappeared, $\Delta\theta$ was increased but $\Delta\omega$ was decreased.

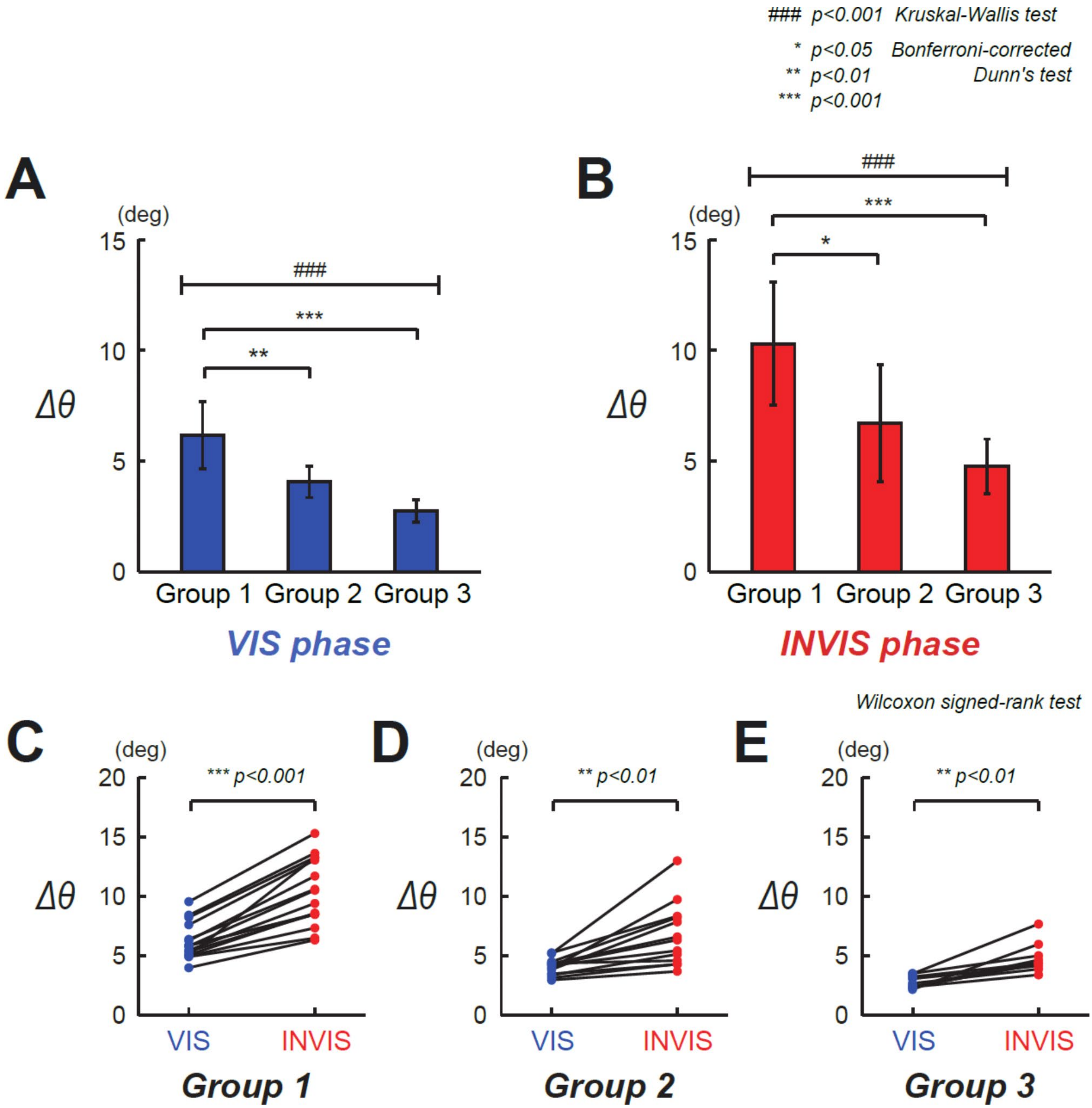

Fig. 6. Statistical hypothesis tests on $\Delta\theta$. Group 1 shows significantly larger $\Delta\theta$ than Group 2 and 3 in both (A) VIS and (B) INVIS phases. The error bar represents one standard deviation in each Group. Significant increase in $\Delta\theta$ from VIS to INVIS is reported in (C) Group 1, (D) Group 2, and (E) Group 3.

Variable	N	Test Statistic	df	Sig.	Effect size, η^2	Power
$\Delta\theta$ VIS	39	***28.066	2	8.05×10^{-7}	0.724	0.999
$\Delta\theta$ INVIS	39	***21.072	2	2.66×10^{-5}	0.530	0.999
$\Delta\omega$ VIS	39	***17.513	2	1.58×10^{-4}	0.431	0.998
$\Delta\omega$ INVIS	39	***19.780	2	5.07×10^{-5}	0.494	0.999

Table 1. Kruskal-Wallis Test.

Variable	Pairwise		Test Statistic	Std. Error	Std. Test Statistic	Adjusted Sig.	Effect size, d	Power
$\Delta\theta$ VIS	Group 1	Group 2	13.115	4.257	**3.081	0.006	1.395	0.940
	Group 2	Group 3	10.785	4.796	2.249	0.074	1.062	0.651
	Group 3	Group 1	23.900	4.596	***5.200	5.98×10^{-7}	44.688	0.999
$\Delta\theta$ INVIS	Group 1	Group 2	12.452	4.257	*2.925	0.010	1.293	0.902
	Group 2	Group 3	7.923	4.796	1.652	0.296	0.733	0.368
	Group 3	Group 1	20.375	4.596	***4.433	2.79×10^{-5}	3.512	0.999
$\Delta\omega$ VIS	Group 1	Group 2	0.736	4.257	0.173	0.999	0.064	0.053
	Group 2	Group 3	17.077	4.796	**3.561	0.001	2.227	0.998
	Group 3	Group 1	17.813	4.596	***3.875	3.19×10^{-4}	2.339	0.999
$\Delta\omega$ INVIS	Group 1	Group 2	2.567	4.257	0.603	0.999	0.225	0.088
	Group 2	Group 3	17.008	4.796	**3.546	0.001	2.194	0.998
	Group 3	Group 1	19.575	4.596	***4.259	6.16×10^{-5}	3.035	0.999

Table 2. Dunn's test of pairwise multiple comparisons with Bonferroni Adjustment.

Paired Variables		*N*	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Effect size, d	Power
$\Delta\theta$ VIS, $\Delta\theta$ INVIS	Group 1	16	136	19.339	***3.516	4.38×10^{-4}	2.422	0.999
	Group 2	13	91	14.309	**3.180	0.001	1.215	0.974
	Group 3	10	55	9.811	**2.803	0.005	1.777	0.998
$\Delta\omega$ VIS, $\Delta\omega$ INVIS	Group 1	16	31	19.339	-1.913	0.056	0.519	0.472
	Group 2	13	1	14.309	**-3.110	0.002	1.295	0.986
	Group 3	10	4	9.811	*-2.395	0.017	0.973	0.758

Table 3. Wilcoxon Signed-Rank Test.

Statistical hypothesis tests on $\Delta\omega$

Figure 7 summarizes the statistical tests on $\Delta\omega$ according to the three age groups (a between-subject factor) and the visibility condition of the target (a within-subject factor).

Figure 7A shows the difference in $\Delta\omega$ among Groups in the VIS phase. The means and standard deviations are 20.46 ± 2.88 deg/s for Group 1, 19.82 ± 4.50 deg/s for Group 2, and 12.85 ± 2.03 deg/s for Group 3. The Kruskal-Wallis test in Table 1 reports that Groups have statistically different means in the VIS phase ($p = 1.58\times10^{-4}$). The Bonferroni-corrected Dunn's tests for post-hoc multiple comparisons in Table 2 reveal that Group 3 has significantly smaller $\Delta\omega$ than Groups 1 and 2 ($p = 3.19\times10^{-4}$ between Groups 1 and 3; $p = 0.001$ between Groups 2 and 3). In addition, $\Delta\omega$ of Group 2 was not statistically different from that of Group 1 ($p = 0.999$ between Groups 1 and 2). It signifies that the velocity feedback control ability grows with age, but no significant improvement up to an adult level is observed in preteens.

Figure 7B illustrates the difference in $\Delta\omega$ among Groups in the INVIS phase. The means and standard deviations are 18.91 ± 3.34 deg/s for Group 1, 17.44 ± 3.53 deg/s for Group 2, and 11.77 ± 1.08 deg/s for Group 3. The Kruskal-Wallis test in Table 1 reports that Groups have statistically different means in the INVIS phase ($p = 5.07\times10^{-5}$). The Bonferroni-corrected Dunn's tests for post-hoc multiple comparisons in Table 2 reveal that Group 3 again has significantly smaller $\Delta\omega$ than Groups 1 and 2 ($p = 6.16\times10^{-5}$ between Groups 1 and 3; $p = 0.001$ between Groups 2 and 3). Furthermore, $\Delta\omega$ of Group 2 was not statistically different from that of Group 1 ($p = 0.999$ between Groups 1 and 2). It implies that the velocity predictive control ability grows with age, but no significant improvement up to an adult level is found in preteens.

Figure 7C and D, and 7E present the difference in $\Delta\omega$ regarding the visibility condition of the target within each Group. The Wilcoxon signed-rank tests in Table 3 suggest that Group 1 has shown no difference in $\Delta\omega$ regardless of the visibility condition of the target ($p = 0.056$ within Group 1). However, Groups 2 and 3 have shown significantly smaller $\Delta\omega$ during the INVIS phase ($p = 0.002$ within Group 2; $p = 0.017$ within Group 3). The results imply that the younger children faced difficulties matching the velocity of the tracer and the target in both phases, while the older children and adults successfully reproduced the velocity from memory during the INVIS phase. Thus, it appears that the speed control abilities begin to develop in preteens but are still immature compared to adults.

Discussions

Our objective was to compare motor control characteristics between children and adults in a wrist tracking task and to identify the age-related developmental process. We had the three age groups as a between-subject factor and the visibility condition of the target as a within-subject factor. The absolute angular position difference $\Delta\theta$ and absolute angular velocity difference $\Delta\omega$ were computed to evaluate the position and velocity control

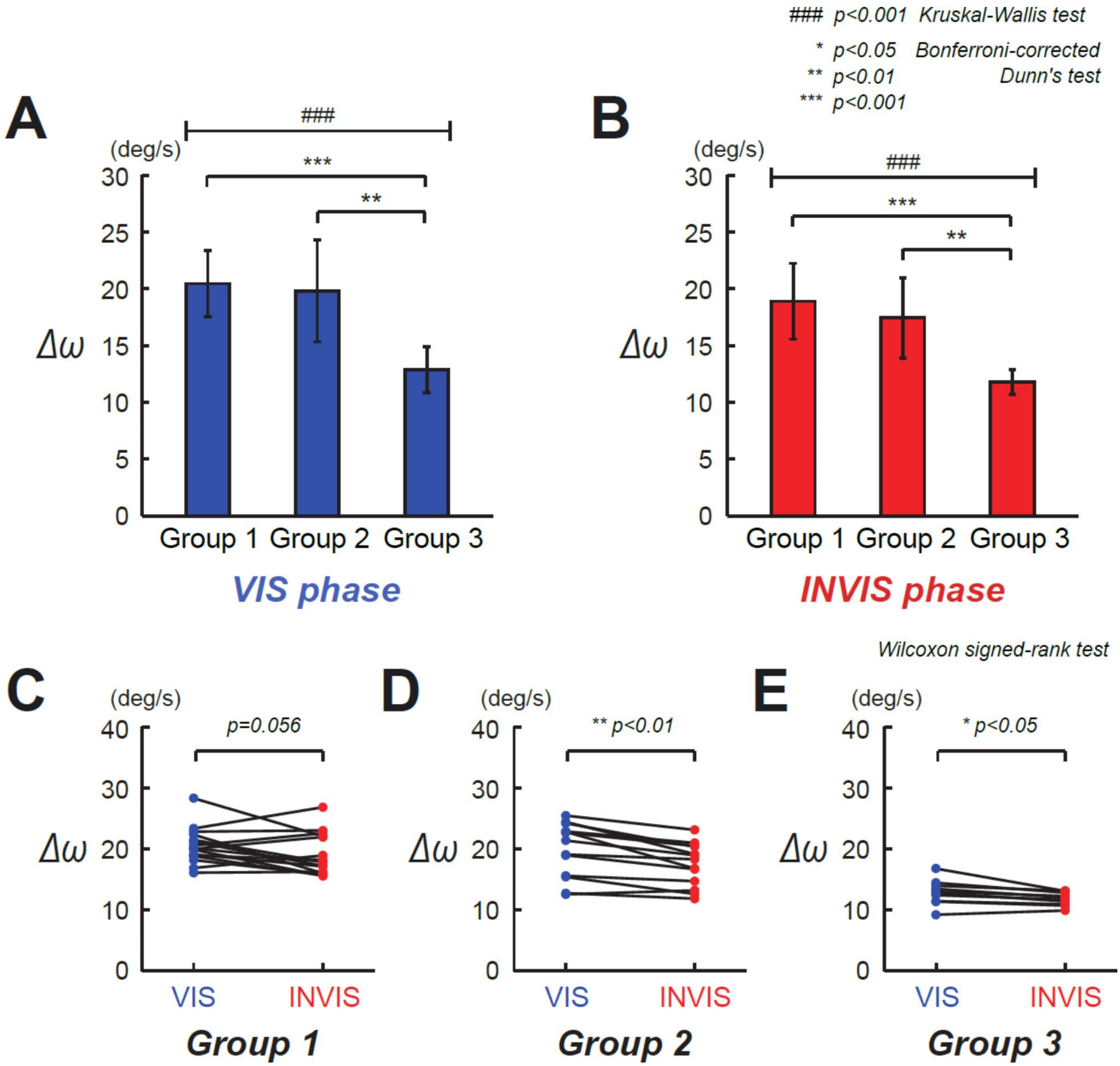

Fig. 7. Statistical hypothesis tests on $\Delta\omega$. Group 3 has significantly smaller $\Delta\omega$ than Group 1 and 2 in both (A) VIS and (B) INVIS phases. The error bar represents one standard deviation in each Group. No significant change in $\Delta\omega$ from VIS to INVIS is found in (C) Group 1, but significant decrease in $\Delta\omega$ is reported in (D) Group 2 and (E) Group 3.

abilities. Based on the statistical tests in Tables 1 and 2, and 3, we discovered that the older children (Group 2) showed similar position accuracy to the adults (Group 3) shown in Fig. 6A and B, but their velocity accuracy remained at the level of the younger children (Group 1) presented in Fig. 7A and B. However, we could infer that the older children's velocity control abilities were developing because they managed to decrease $\Delta\omega$ when the target disappeared as the adults did in Fig. 7D and E. The presence of the target had positive effects on the position accuracy for all Groups shown in Fig. 6C and D, and 6E but negative impacts on the velocity accuracy for Groups 2 and 3 depicted in Fig. 7D and E. It indicates that the position control depends more on visual feedback, whereas the velocity control relies more on feedforward and state estimation by internal models. Thus, we could summarize that preteen children's feedback skills are almost grown, but their feedforward skills are just beginning to develop.

Mounoud et al. were one of the earliest research groups to conduct tracking tasks with children in 1985[16]. They observed sinusoidal elbow movements in 5-to 9-year-old children and calculated phase and frequency errors to evaluate their position and velocity control abilities. The researchers noticed that the phase error gradually decreased with age and concluded that visuomotor coordination develops during childhood. However, they emphasized that the size of the phase error was incomparable to that of adults as our analysis on $\Delta\theta$ between

Groups 1 and 3. Zanone expanded the findings of Mounoud et al. by conducting the same research in 9-to 15-year-old children in 1990[17]. The older children produced comparable phase errors to adults when tracking with a visible target but made greater frequency errors with an invisible target than the adults. The former agrees with our $\Delta\theta$ result between Groups 2 and 3, whereas the latter with $\Delta\omega$ between the Groups. Therefore, our research and the earliest studies make an analogous statement that the position control ability is almost developed around preteens and the velocity control ability thereafter.

Recent studies also support the statement regarding motor control development. Van Roon et al. conducted a tracking task using a digital pen and tablet in 2008 and examined motor characteristics of children between 6 and 17 years old[18]. The researchers discovered that the feedback-based step-and-hold strategies gradually disappear, and the feedforward-based smooth movements emerge around 10 and 11 years, which correspond to the borderline between Groups 1 and 2 in our study. They indicated the matured cerebellum and internal models in older children as one of the main reasons behind the change in control strategies. In 2015, Ferguson et al. reported that 6- to 10-year-old children with developmental coordination disorder (DCD) were less prominent than typically developing children in tracking tasks especially with a fast and invisible target which required feedforward controls[19]. Because fMRI studies reported lower cerebellum activation in children with DCD[26,27], the researchers suggested that the children had difficulty predicting the target and arm movements due to relatively immature internal models in the brain. On the contrary, we could infer that feedforward skills in typically developing children are actively developing around middle and late childhood.

The significant difference between our research and the reference studies is that we have focused on wrist movements, and there are several benefits of investigating the single joint. First, it is easy to restrict the movement of joints other than the wrist during the experiment. Using electronic pens and tablets, Van Roon et al. and Ferguson et al. observed complex movements involving the fingers, wrist, and elbow[18,19]. Because of the redundant degrees of freedom (DOFs) in humans[2,5], motor planning and execution processes could be investigated more precisely by reducing the DOFs to the musculoskeletal system of interest. Second, the wrist can make continuous rotational motions. Mounoud et al. and Zanone achieved the simplicity in DOF by conducting elbow-tracking tasks but could only observe sinusoidal movements due to the structural limitations of the elbow joint[16,17]. Because the elbow should completely stop and then accelerate to the opposite direction for a back-and-forth motion, it is difficult to design a tracking task with a target continuously moving at a fixed speed. Concerning the wrist, the target speed could be accelerated, decelerated, or constant as well as the shape of its trajectory could be freely designed[22,28–30]. Lastly, since the weight of a human hand is light, the effects of gravity and inertia on the wrist joint are often negligible compared to other joints. More recent studies on human motors utilize new platforms such as VR and report meaningful results[31,32]. Since they usually investigate arm movements, the external and internal disturbances would influence desired motions. Along with the redundant DOF, the disturbances often become obstacles in deducing mathematical models for human motor control. To compensate for the undesired effects and suggest convincing inverse kinematics of the human arm, researchers in the 1980s and 1990s conducted simple point-to-point reaching tasks mostly on the transverse plane using rigid workstations with an armrest[33,34]. In wrist movements, the influence of rotational inertia is relatively negligible[28,35]. We are now working on to derive a simpler computational model based on our tracking task and the state variables $\Delta\theta$ and $\Delta\omega$ to reveal secrets behind human motor control and replicate human-like movements by simulation.

Exploring beyond the target-tracking studies, we could find more evidence that preteen children are actively developing feedforward abilities and internal models in terms of speed perception, joint localization, and force adaptation[21,36,37]. Manning et al. reported that a child's ability to distinguish faster speeds reaches adult levels by age 11[21]. Accordingly, we could infer that children's velocity-based feedforward skills are gradually developing along with the sensitivity to slower speeds during preteens and adolescence. Contreras-Vidal discovered that 10-year-old children were more accurate and precise at proprioceptive localization of the hand than younger children and even comparable to adults[36]. Jansen-Osmann et al. suggested that adequate and fast adaptation to external forces is achieved at least in late childhood because only 10-year-old children took about three or four trials to adapt to damping forces and null forces on their arms like adults did[37]. Hence, we could also infer that internal models for anticipation of body movements and environmental influences are actively developing in preteens. Then, older children would produce more accurate feedforward controls based on the matured internal models. Because the process involves a series of perceiving current states and computing desired motor commands, we want to point out that motor planning skills are also actively developing in preteens. The end-state comfort tasks designed by Scharoun Benson et al. for motor planning study support our conjecture since 10-year-old children showed adult-like patterns such as functional grasp postures unlike 8- to 9-year-old children[38]. In summary, it is notable that the preteen criterion, which we have suggested as a starting line for feedforward skills, repeatedly appears in various studies regarding children's motor development.

Regarding the wrist tracking task, the preteen criterion may be slightly decreased due to its simplicity in movements, as discussed earlier. Given the p-value of 0.056 for $\Delta\omega$ within Group 1 in our results, increasing the sample size can alter the Wilcoxon signed-rank test in Table 3 and lead to a conclusion that meaningful feedforward controls are also performed by 7- to 9-year-old children. However, from the medium effect size ($d=0.519$) and low statistical power ($1\text{-}\beta=0.472$), we concluded that the near significance is not effective enough. Furthermore, gender effects may exist concerning motor abilities within the younger children as in Junaid and Fellowes' research with 103 children[39], but we found no notable differences in terms of $\Delta\theta$ and $\Delta\omega$ based on Mann-Whitney tests between our 10 male and 6 female subjects in Group 1 ($\Delta\theta$ VIS: $p=0.428$, $\Delta\theta$ INVIS: $p=0.492$, $\Delta\theta$ VIS: $p=0.368$, $\Delta\theta$ VIS: $p=0.635$). Considering the p-value on the borderline, possible gender effects, and limitations stated in Methods, we have made more careful conclusion based on the wrist tracking task that children develop feedforward abilities and internal models from their preteens between 10 and 12 years rather than our strict initial age-10 criterion. Since the results were limited to a wrist tracking task in in children between 7 and 12, our conclusions should be validated by future studies with other movement tasks and wider age ranges.

Data availability

The datasets used and/or analyzed during the present study are available from the corresponding authorsupon reasonable request.

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Author contributions

Jihun Kim: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review and Editing, Visualization; Jongho Lee: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data Curation, Writing - Review & Editing, Visualization, Supervision; Jaehyo Kim: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics declarations

The research was approved by the ethics committees of Handong Global University (2022-HGUA020) and conducted under the ethical standards of the Declaration of Helsinki. All subjects were fully informed about the research and provided written informed consent before the experiment.

Additional information

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