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Original Paper

Developmental Changes in Finger Motor Control During Musical Expression in Early Childhood: A Quantitative Analysis Using Wearable Motion Capture

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Abstract

This study investigates developmental changes in finger motor control during musical expression, focusing on metacarpal level movement. A total of 86 children aged 3-5 years participated. Finger movements were recorded using wearable motion capture technology (Meta gloves) synchronized with a 3D motion capture system. Two kinematic indicators such as total moving distance and moving average acceleration were extracted and analyzed. Statistical analyses included three-way and two-way ANOVA with facility, melody type, and age as factors, and linear mixed-effects models.

Results revealed (1) functional differentiation among metacarpals, with the fourth and fifth metacarpals exhibiting significantly greater movement magnitude and acceleration; (2) developmental increases in both indicators with age; and (3) significant effects of musical characteristics, with bright melodies and imaginative songs eliciting greater motor responses.

These findings demonstrate that fine motor dynamics are systematically related to both developmental progression and musical structure. The study provides objective indicators of embodied musical expression and offers a foundation for approaches informed data in early childhood music education.

Keywords

musical expression in early childhood, motor development, fine motor skills, embodied learning, finger movement, quantitative analysis

1. Introduction

1.1 Literature Review

Musical expression is fundamentally embodied. Musical expression arises from the dynamic interaction between elements such as perception, behavior, cognition, and emotion, through the act of experiencing music. Contemporary theory in the related field shows that bodily movement is not merely incidental to musical activity, but rather an essential component of musical perception and expression (Leman, 2007; Maes et al., 2014). Various evidence in the related studies has demonstrated that musical structure systematically influences body movement. Characteristics such as rhythm, tempo, meter, and timbre evoke distinct movement patterns, indicating close relationships between auditory processing and motor behavior (Burger et al., 2013; Toiviainen et al., 2010). Studies of music performance have further shown that bodily movement conveys expressive information beyond the acoustic signal itself and plays an important role in communication between performers and audiences (Thompson & Luck, 2012; Wanderley et al., 2005). These findings have influenced research in the field of music, making it possible to view movements as an important element.

Recent advances in motion capture technology have proceeded detailed investigation of body movement musical expression. Quantitative analyses have been used to examine performer gestures, motor coordination, movement efficiency, and expressive communication during music performance (Goebl & Palmer, 2013; Bishop et al., 2019). Research based on such approaches can quantify kinematic variables including the moving distance, the moving velocity, the moving acceleration, and temporal coordination, and provide objective measures of expressive behavior as well as traditional observational approaches.

Among the various components of musical movement, hand and finger actions have an important position. Fine motor control of the fingers enables precise timing, articulation, and expressive nuance in many musical activities. Previous studies have demonstrated that finger movement efficiency is closely associated with performance expertise and motor coordination (Goebl & Palmer, 2013). Research in motor neuroscience has shown that individual fingers possess distinct biomechanical and neuromotor characteristics and contribute differently to complex movement patterns (Furuya & Altenmüller, 2013; Liu et al., 2021). In the related field of music, emotional and psychological factors have also been shown to influence finger movement, and the sensitivity of finger motor control to expressive demands (Kotani & Furuya, 2018). Visual processes are similarly involved in the musical behavior. Eye-tracking studies have revealed important relationships between gaze behavior, attention, and musical interaction during musical performance (Bishop et al., 2019; Vandemoortele et al., 2018). Furthermore, research on eye-hand coordination has demonstrated that the coordination of vision and hand movements constitutes a fundamental mechanism of motor learning and fine motor development (Bonnet et al., 2019; Park et al., 2023). A recent systematic review concluded that eye and hand coordination plays a central role in upper-limb motor control and advocated the need for further quantitative investigations using objective movement measures (Abid et al., 2025).

In spite of progression of music performance research, most quantitative investigations of hand and finger movements have focused on adult musicians and expert performers. Few research reported about the development of finger motor control during musical expression in early childhood although early childhood represents a critical period for the development of sensorimotor integration, manual dexterity, and expressive movement. Previous research has shown that music training can positively influence children's manual dexterity and bimanual coordination (Martins et al., 2018), suggesting close relationships between musical activity and motor development. However, objective kinematic analyses are scarcely observed in finger movements during natural musical expression in early childhood. Wearable motion capture systems provide new opportunities to address this gap. Compared to conventional observation methods, using wearable sensors allows for continuous and highly accurate measurement of movement characteristics in everyday environments. By quantifying the moving distance, the moving velocity, and the moving acceleration of individual finger segments, it becomes possible to identify developmental differences and functional characteristics that are difficult to verify through only visual observation.

1.2 Research Question

The present study investigates developmental characteristics of finger motor control during musical expression in early childhood using wearable motion capture technology. Previous research in the author's study has demonstrated that feature quantities extracted from movement analysis of musical expression, implemented into machine learning models improved the classification accuracy of developmental stages in musical expression, reaching to 74.42% (Sano, 2024). Additionally, integrating eye movement data has revealed that the body and gaze behaviors vary significantly depending on musical characteristics such as melody (Sano, 2021-2023). Based on the previous studies, this study focuses on the differences among individual fingers and finger segments in order to clarify their functional contributions to musical expression. Through quantitative analyses of the moving distance, the moving velocity, and the moving acceleration, this study aims to provide objective evidence regarding the motor organization of musical expression in early childhood and to contribute to various discussions of embodied musical behavior, motor development during musical expression.

To address this gap, the present study focuses on movement of metacarpal level and investigates how finger motor control develops in response to musical stimuli in early childhood. Using wearable motion capture technology, this study aims to establish objective, quantitative indicators of motor behavior in musical expression.

The research questions are as follows:

(1) How do finger movement characteristics change with age during musical expression?

(2) How do musical features influence finger motor dynamics?

(3) Are there functional differences among metacarpals in expressive movement in musical expression?

By addressing these questions, this study contributes to developmental science and early childhood education by providing a framework driven on the data for understanding embodied musical expression. If new feature quantities were extracted through this process and improve the accuracy of our machine learning, it will be able to present objective indicators that quantitatively capture the developmental process of musical expression in early childhood. This research thought to be necessary from the viewpoint of which will provide even inexperienced early childhood educators more useful information to decide how to provide effective musical experiences for early childhood children.

1.3 Purpose

This study aims to clarify the characteristic changes in the movement of each metacarpal bone of the five fingers during musical expression in early childhood. For this purpose, the author attempted to scrutinize the characteristics of the total moving distance and the moving average acceleration of the metacarpal bones of the five fingers through quantitative analysis.

2. Method

2.1 Participants

Eighty-six children aged 3-5 years participated in the study (T: n = 29; W: n = 28; Y: n = 29). All participants were typically developing and engaged in routine musical activities in their respective childcare settings. Informed consent was obtained from guardians, and the study was approved by the institutional ethics committee.

2.2 Apparatus

Finger movements were recorded using wearable motion capture gloves (Meta gloves) integrated with a 3D motion capture system (MVN, Xsens) at a sampling rate of 60 Hz. Sensors were attached to each fingertip, and additional sensors were placed on 11 upper-body locations following the MVN protocol. Each participant wore modified Meta gloves adapted for young children. Sensors were attached to each fingertip to capture fine motor movements. In addition, upper-body motion sensors were placed at 11 standardized anatomical points according to the MVN protocol.

Before data collection, a calibration procedure was conducted for both systems. For the gloves, calibration included three standardized hand movements. For the MVN system, calibration involved an alignment procedure based on walking.

2.3 Procedure

Participants performed musical expression tasks involving singing and finger-play songs familiar within their educational context. Each session lasted approximately 5-6 minutes to ensure ecological validity.

2.4 Variables

From the recorded motion data, 19 kinematic variables were extracted for each finger segment. In the present study, analysis focused on metacarpal level data for all five fingers.

Two primary indicators were analyzed:

・Total moving distance (m)

・The moving average acceleration (m/s²)

These indicators were calculated for each metacarpal across all recorded frames.

2.5 Statistical Analysis

A three-way non-repeated ANOVA (facility × melody × age) and a two-way non-repeated ANOVA (song × age) were conducted. Post hoc analyses were performed where appropriate. Statistical significance was set at $p < .05$.

To examine the effects of developmental and musical factors, the following analyses were conducted: A three-way non-repeated ANOVA with facility (3 levels), melody type (2 levels: bright vs. dark), and age (3 levels) as between-subject factors.

A two-way non-repeated ANOVA with song (multiple levels) and age (3 levels) as factors for selected variables.

All analyses were performed using SPSS29 as a standard statistical software.

Furthermore, metacarpal differentiation was analyzed by linear mixed-effects models with Bonferroni method.

2.6 Measurement Date, Time

The measurement dates and times in 2024 are as follows. The measurement dates and times are as follows.

T facility: June 4, 11, 18, and 25.

W facility: July 2, 5, 9, 12, 23, and 24.

Y facility: September 13 and 27.

2.7 Songs for Measurement

The songs for measurement were mainly selected by the facilities from among those songs that children have musical experiences with during their time at the facility as shown in Table1.

Table 1. Songs to Be Measured at Each Facility in 2024

	T facility (n=29)	W facility (n=28)	Y facility (n=26)
melody songs	melody (bright) Tontontonhigejiisan (Lyrics: unknown / Music: Tamayama Hidemitsu) Guchokipadenanitsukurou (French folk song) Panyasanniokaimono (Lyrics: Sakura Tomoko / Music: Ozawa Tatsuyuki)	melody (bright) Tokeinouta (Lyrics: Keisuke Tsutsui / Music: Taro Murakami) Panyasanniokaimono (Lyrics: Tomoko Sakura / Music: Tatsuyuki Ozawa) Yamanoongakuka (German folk song,	Melody (bright) Kaerunouta (German song/ translation: Toshiaki Okamoto) Yamanoongakuka (German folk song/translation: Shisen Mizuta)

	Yamanoonngakuka(German folk song, translated by Mizuta Shisen)	Translated by Shisen Mizuta)	
melody songs	melody（dark） Agarimesagarime (Lyrics: Masaru Mizutani / Music: Shinpei Nakayama) Nabe nabe soko nuke (Japanese traditional children's song)	melody（dark） Agarimesagarime (Lyrics: Mizutani Masaru / Music: Nakayama Shinpei) Genkotsuyamanotanuki (Lyrics: Kayama Yoshiko / Music: Komori Akihiro) Nabe nabe soko nuke (Japanese traditional children's song)	melody（dark） Hotarukoi (Lyrics and composition: Tomekichi Mikami) Usagi (Japanese traditional children's song)

3. Result

Based on the previous analysis (Sano, 2025), this study focused on the total moving distance and the moving average acceleration of the metacarpals. Regarding the total moving distance, a three-way non-repeated ANOVA was conducted with facility, melody, and age as factors, and some of the analysis results of the third and fourth metacarpals were characteristic. This was also verified by analysis using a linear mixed model with Bonferroni. Regarding the moving average acceleration, some of the results of a two-way non-repeated ANOVA with melody and age as factors are shown for the movement of the fourth and fifth metacarpals, which were characteristic.

3.1 Changes in The Total Moving Distance of Metacarpals During Musical Expression

3.1.1 Results of A Three-Way Non-Repeated AVOVA for Data on The Total Moving Distance by Metacarpals

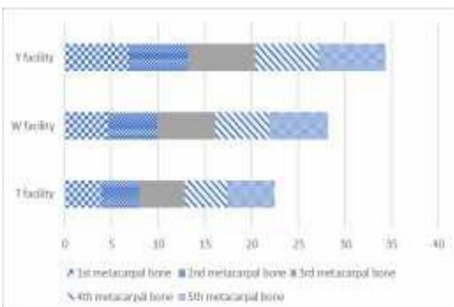
The following Table 2 shows the average values of the total moving distance by metacarpals in five fingers for all the data acquired.in five fingers during musical expression

Table 2. Average Values of Metacarpals' Data Acquired in Three Facilities (m)

	First metacarpal	Second metacarpal	Third metacarpal	Fourth metacarpal	Fifth metacarpal
Mean ($\underline{X}$)	4.2893	4.3228	5.1320	5.1899	4.1665
SD	2.80746	2.56069	2.91758	2.94362	2.49809

As shown in Table 2, the average values for the third and fourth metacarpal were large. A three-way non-repeated ANOVA was conducted with facility, melody, and age as factors, and the results of the between-subjects effects test for the third metacarpal bone data showed that the main effects were statistically significant in the facility factor ($F(2,402)=16.889$, $p<.05$), melody factor ($F(1,402)=135.761$, $p<.05$), and age factor ($F(2,402)=9.969$, $p<.05$). As a result of the multiple comparison test, for melody (bright), 3-year-old was larger in Y facility than T facility, 4-year-old was larger in Y facility than W facility, and 5-year-old was larger in Y facility than both T and W facilities. 4-year-old was larger in Y facility than W facility in the melody (dark). 5-year-old was larger than 3-year-old by the melodies (light) (dark) in T facility. Regarding the fourth metacarpal data, the between-subjects test showed that the main effects were statistically significant (the facility factor: ($F(2,402)=19.633$, $p<.05$), the melody factor: ($F(1,402)=136.108$, $p<.05$), and the age factor: ($F(2,402)=8.605$, $p<.05$)). As a result of multiple comparison test, 3-year-old was larger in Y facility than T facility for the melody factor (bright), 4-year-old was larger in Y facility than W facility for the melody (bright), 5-year-old was larger in Y facility than T facility and W facilities in the melody (bright). 4-year-old was larger in Y facility than W facility nursery for the melody (dark). 3-year-old,4-year-old, and 5-year-old was larger in the melody (bright) than melody (dark) at T, W, and Y facilities. 5-year-old showed larger sensitivity to the melodies (bright) (dark) than 4-year-old in T facility.

The following Figures 1-1 to 1-6 show the total moving distance of metacarpal across five fingers during musical expression. Those panels (1-6) show results by age group (3-, 4-, and 5-year-olds) and melody condition (bright vs. dark) across three facilities.



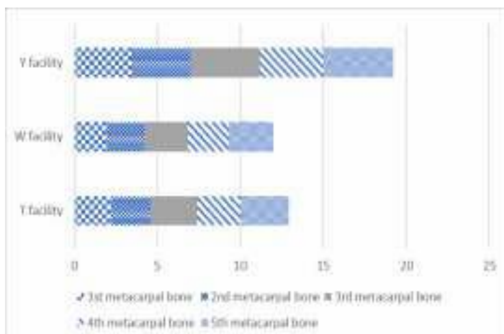


Figure 1-1. 3-Year-Old: The Moving Distance of Metacarpal Distance of Across Five Fingers During Musical Expression (m) Musical (Melody: Bright)

Figure 1-2. 3-Year-Old: The Moving Metacarpal Across Five Fingers During Expression (m) (Melody: Dark)

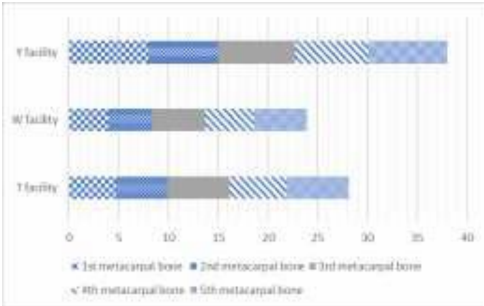


Figure 1-3. 4-Year-Old:The Moving Distance of Metacarpal Distance of Across Five Fingers During Musical Expression (m) Musical (Melody: Bright)

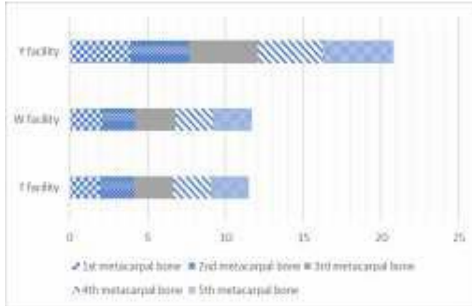


Figure 1-4. 4-Year-Old: The Moving Metacarpal Across Five Fingers During Expression (m) (Melody: Dark)

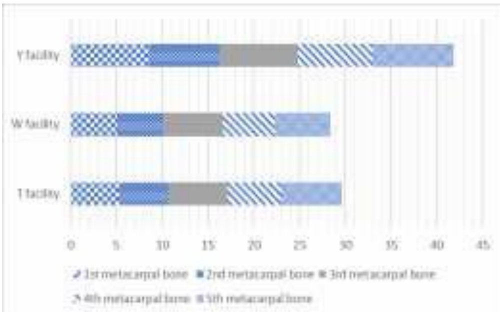


Figure 1-5. 5-Year-Old: The Moving Distance of Metacarpal Distance of Across Five Fingers During Musical Expression (m) Musical (Melody: Bright)

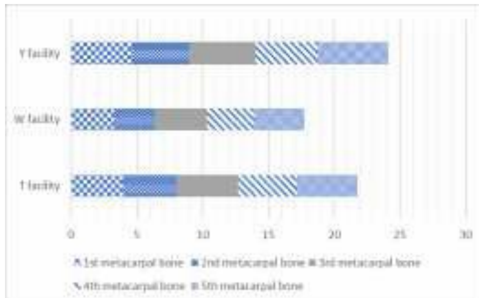


Figure 1-6. 5-Year-Old: The Moving Metacarpal Across Five Fingers During Expression (m) (Melody: Dark)

As shown in Figures 1-1 to 1-6, the total moving distance was larger for the melody (bright) in all five metacarpals, and 5-year-old was larger than 3-year-old. Any significant difference was not observed in the ratio of each metacarpal bone to the total moving distance in any facility, and the total moving distance was significantly larger in Y facility than in W and T facilities. Overall, the moving distance increased with age and was consistently greater in the bright melody condition across all metacarpals.

3.1.2 Results of Principal Component Analysis and Cluster Analysis

Principal component analysis and cluster analysis were conducted on the metacarpal data of the fifth finger. The cluster analysis showed that the data was largely divided into the first metacarpal and the rest, followed by the second metacarpal and the third metacarpal, and then the third metacarpal and the fourth and fifth metacarpals. The closest are the fourth and fifth metacarpals, which are related to more detailed rhythms and imagery of movement, while the furthest is the first metacarpal, which creates movements that respond to the recognition of beats and rhythm, and which, together with the second metacarpal, is connected to evoking movements shaping the imagery of the lyrics. As a result of the principal component analysis, the first three principal components had an explanatory power of 99.663%, and from the principal component score coefficient matrix, it was inferred that the first principal component, with all positive factor loadings, represents movements that support basic finger movements, the second principal component, with a positive factor loading only on the first metacarpal, represents beat and rhythm movements, and the third principal component, with a notable positive factor loading on the third metacarpal, represents movements forming images. Figure1-7 shows hierarchical cluster analysis of metacarpal movement patterns. The dendrogram illustrates the similarity structure among metacarpals based on movement features.

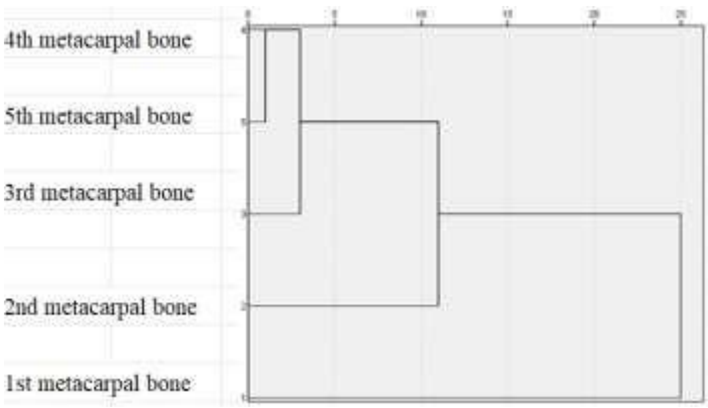


Figure 1-7. Dendrogram of Hierarchical Cluster Analysis of Metacarpal Movement Patterns.

3.2 Characteristics of Changes in The Moving Average Acceleration in The Metacarpal of Five Fingers

3.2.1 Average Value of The Moving Average Acceleration in The Metacarpal of Five Fingers Figure 2-1 shows the moving average acceleration of metacarpal movements across five fingers. Mean values are shown with standard deviations.

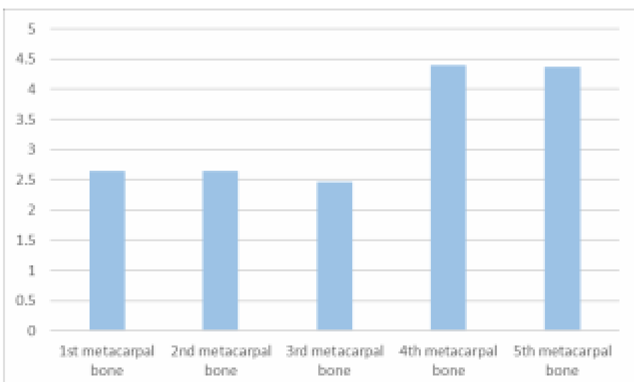


Figure 2-1. The Moving Average Acceleration of Metacarpal Movements of Across Five Fingers (m/s^2)

As shown in Figure 2-1, regarding the moving average acceleration of the metacarpals, the average value of the first metacarpal was 2.6408m/s^2 (*SD*=2.1817), the average value of the second metacarpal was 2.6456m/s^2 (*SD*=2.06023), the average value of the third metacarpal was 2.4595m/s^2 (*SD*=2.02995), the average value of the fourth metacarpal was 4.3935m/s^2 (*SD*=2.96410), and the average value of the fifth metacarpal was 4.3714m/s^2 (*SD*=2.95220), and the sizes of the fourth and fifth metacarpals were remarkable. The fourth and fifth metacarpals exhibited higher acceleration values compared to other fingers. Age-related increases were observed, particularly in response to rhythmically active and imaginative songs.

3.2.2 Changes in The Moving Average Acceleration of Each Metacarpal in The Fifth Finger due to The Song

Figure 2-2 shows the changes and characteristics of the moving average acceleration of metacarpal in the fifth finger for 3-year-old children due to the song. The names of the songs are shortened, such as "Genkotsuyama no Tanuki" to "Genkotsu".

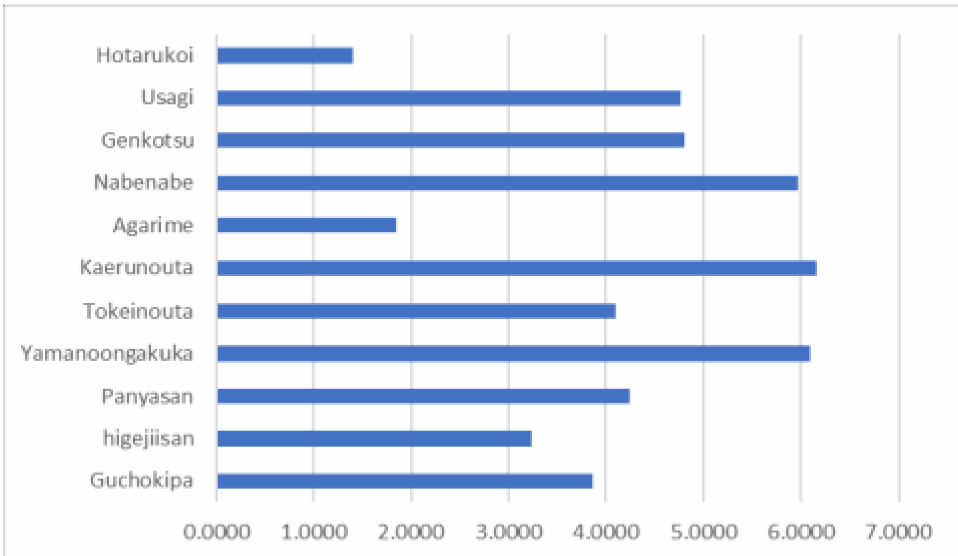


Figure 2-2. The Moving Average Acceleration of The Metacarpal of The Fifth Finger for 3-Year-Old Child (m/s^2)

As shown in Figure 2-2, the moving average acceleration of the metacarpals was remarkable for "Kaerunouta," followed by "Yamanoongakuka." The moving average acceleration of 3-year-old was also large for Japanese traditional children's songs in which the lyrics induced movements in time with the beat and pretend movements related to the image of an event. For each metacarpal, the third, fourth, and fifth metacarpals were large, and this tendency was also observed in 5-year-old.

3.2.3 Results of Two-Way Non-Repeated ANOVA of Moving Average Acceleration Data for The Fourth and Fifth Metacarpals

3.2.3.1 Results of Two-Way Non-Repeated ANOVA of The Moving Average Acceleration Data for The Fourth Metacarpal

A two-way non-repeated ANOVA was conducted on the moving average acceleration data for the fourth metacarpal bone, with the factors of song and age. A result of between-subject effects test showed that the main effect was significant in the song factor ($F(10, 387)=8.807$, $p<.05$). As a result of multiple comparison test, 3-year-old was large in "Panyasanniokaimono", "Nabenabesokonuke", and "Genkotsuyamanotanuki", while 4-year-old and 5-year-old was large in "Yamanoongakuka", 5-year-old was large in "Kaerunouta". 3-year-old was larger than 4-year-old for "Genkotsuyamanotanuki".

3.2.3.2 Results of Two-Way Non-Repeated ANOVA of The Moving Average Acceleration Data for The Fifth Metacarpal

A two-way non-repeated ANOVA was conducted on the average values of the moving average acceleration data for the fifth metacarpal, with the factors of song and age. A result of between-subject effects test showed that the main effects were statistically significant in the song factor ($F(10, 387) = 10.788$, $p < .05$) and the age factor ($F(2,402) = 3.286$, $p < .05$). As a result of the multiple comparison test, in terms of the song factor, 3-year-old was large in "Yamanoongakuka" and "Kaerunouta'', and "Nabenabesokonuke'' was large. 4-year-old and 5-year-old were large in "Yamanoongakuka" and "Kaerunouta".

The following Figure 2-3 shows the change in moving average acceleration at the fourth metacarpal bone by age for each song. Changes in moving average acceleration of the fourth metacarpal by age for each song.

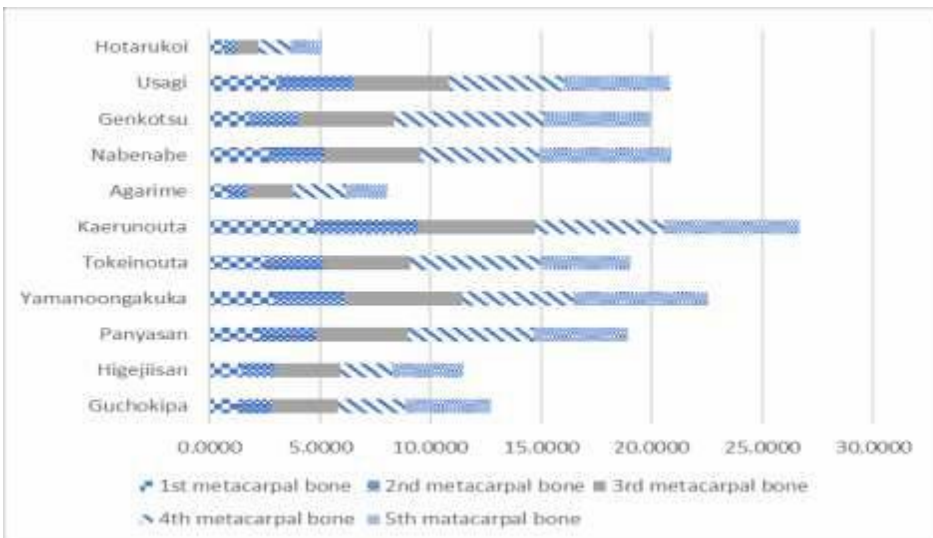


Figure 2-3. Changes in The Moving Average Acceleration of The Fourth Metacarpal Bone for Each Song (m/s^2)

Each song has its own image based on the lyrics, as the results of two-way non-repeated ANOVA and Figure 2-3, the magnitude of the moving average acceleration at the fourth metacarpal increased from 3-year-old to 5-year-old was remarkable for "Kaerunouta," followed by "Yamanoongakuka" and "Panyasanniokaimono," which were larger than "Hotarukoi," and several songs were thought to be due to their bright melodies. It was found that even when the lyrics of nursery rhymes such as "Nabenabe sokonuke" and "Genkotsuyamanotanuki" evoked large body movements, the moving average acceleration at the fourth metacarpal increased in 5-year-old children, whose comprehension of the lyrics was improving.

Those above results revealed distinct differences in movement characteristics across metacarpals. The third and fourth metacarpals showed the largest total moving distances. A three-way non-repeated ANOVA indicated significant main effects of facility, melody, and age for both the third and fourth metacarpals ($p < .05$).

Across all age groups, total moving distance was greater in the bright melody condition than in the dark condition. Additionally, movement magnitude increased with age, with 5-year-old children exhibiting significantly greater values than 3-year-olds.

Cluster analysis demonstrated that the fourth and fifth metacarpals formed a closely related group, whereas the first metacarpal was functionally distinct. Principal component analysis indicated that the first component reflected general movement, the second rhythmic movement, and the third imaginative movement.

3.3 Metacarpal Movement Characteristics Across Fingers

To investigate finger-specific characteristics of metacarpal movement during musical expression, separate linear mixed-effects models (LMMs) were fitted for the moving distance, the moving average velocity, the moving average acceleration, and the moving smoothness. Finger (first-fifth) was entered as a fixed effect and participant as a random effect. Next, Bonferroni-adjusted pairwise comparisons were conducted.

Linear mixed-effects models were conducted to examine differences in metacarpal movement among the five fingers. Finger was entered as a fixed effect, and participant/row was treated as a random intercept. Separate models were fitted for moving distance, moving average velocity, moving average acceleration, and smoothness. Bonferroni-adjusted pairwise comparisons were conducted. A significant main effect of finger was found for all four variables: the moving distance, Wald $\chi^2(4) = 877.15$, $p < .001$; the moving average velocity, Wald $\chi^2(4) = 947.91$, $p < .001$; the moving average acceleration, Wald $\chi^2(4) = 498.37$, $p < .001$; and the moving smoothness, Wald $\chi^2(4) = 938.29$, $p < .001$.

Table 3 shows the estimated marginal means for each finger.

Table 3. Estimated Marginal Means for Each Finger

Variable	Finger	EMM	SE	95% CI
Moving distance	First	4.289	0.138	[4.018, 4.560]
	Second	4.323	0.138	[4.052, 4.594]
	Third	5.132	0.138	[4.861, 5.403]
	Fourth	5.19	0.138	[4.919, 5.461]
	Fifth	5.149	0.138	[4.878, 5.420]
Moving average velocity	First	0.284	0.009	[0.267, 0.301]

	Second	0.29	0.009	[0.273, 0.306]
	Third	0.342	0.009	[0.325, 0.359]
	Fourth	0.346	0.009	[0.329, 0.363]
	Fifth	0.343	0.009	[0.327, 0.360]
Moving average acceleration	First	2.641	0.138	[2.370, 2.911]
	Second	2.646	0.138	[2.375, 2.916]
	Third	4.54	0.138	[4.269, 4.811]
	Fourth	4.393	0.138	[4.123, 4.664]
	Fifth	4.371	0.138	[4.101, 4.642]
Moving smoothness	First	0.119	0.002	[0.115, 0.123]
	Second	0.119	0.002	[0.116, 0.123]
	Third	0.086	0.002	[0.082, 0.090]
	Fourth	0.088	0.002	[0.084, 0.091]
	Fifth	0.087	0.002	[0.083, 0.091]

As a result of Bonferroni-adjusted pairwise comparisons, for moving distance, the third, fourth, and fifth fingers showed significantly greater values than the first and second fingers, all $ps < .001$. No significant differences were found between the first and second fingers or among the third, fourth, and fifth fingers. The same pattern was observed for the moving average velocity and the moving average acceleration. Specifically, the third, fourth, and fifth fingers showed significantly greater velocity and acceleration than the first and second fingers, all $ps < .001$, whereas no significant differences were observed among the third, fourth, and fifth fingers.

In contrast, the moving smoothness showed that the first and second fingers demonstrated significantly greater moving smoothness than the third, fourth, and fifth fingers, all $ps < .001$. No significant difference was observed between the first and second fingers or among the third, fourth, and fifth fingers.

Across the four metacarpal movement indices, a consistent distinction emerged between the radial-side fingers and the ulnar-side fingers. The third, fourth, and fifth fingers were characterized by greater moving distance, moving velocity, and moving acceleration, whereas the first and second fingers were characterized by greater moving smoothness.

4. Discussion

This study provides quantitative evidence that fine motor dynamics during musical expression reflect both developmental progression and musical characteristics in early childhood. By focusing on the movement of metacarpal level, the present findings extend previous research that has primarily examined whole-body motion or gaze behavior.

In this article, the author presented some of the results of a quantitative analysis regarding finger movements analyzed by Meta gloves, focusing on the calculated data of the total moving distance and moving average acceleration of each metacarpal bone for the five fingers. The results revealed that metacarpal movements reflect both developmental progression and musical characteristics in early childhood.

First, the results indicate functional differentiation among metacarpals. The first metacarpal appears to support basic rhythmic coordination, whereas the fourth and fifth metacarpals contribute to more refined expressive and imaginative movements. This interpretation is supported by ANOVA, cluster, and LMM analysis in this study. It was found that the main effects of facility, melody, and age were significant, and that the total moving distance with a bright melody was larger than that dark melody, was larger in 5-year-old than 3-year-old, and was most remarkable in Y facility. This tendency was also observed in the movements of the metacarpals of the other fingers. The first metacarpal was primarily associated with basic rhythm recognition, whereas the fourth and fifth metacarpals supported fine motor expression related to rhythm and imagery. The results of the cluster analysis showed that those measurement sites were roughly divided into the first metacarpal and the rest, with the fourth and fifth metacarpals being the closest, and that these were related to more detailed rhythms and imagery movements. The first metacarpal, which is the furthest away from the others, creates movements that correspond to the recognition of beats and rhythms, and at the same time, together with the second metacarpal, is connected to evoking movements forming the imagery appeared in the lyrics. The results of the principal component analysis suggested that the first principal component represents movements supporting basic finger movements, the second principal component represents beats and rhythms, and the third principal component represents movements forming images.

Second, movement magnitude and the moving average acceleration increased with age, suggesting progressive refinement of motor control.

The average values for the fourth metacarpals in the moving average acceleration of each metacarpal of the five fingers were significantly larger, a two-way non-repeated ANOVA was conducted with factors of song and age. These findings align with developmental theories emphasizing increasing coordination and efficiency in early childhood.

Third, musical characteristics significantly influenced motor behavior. Bright melodies and imaginative songs elicited greater movement responses, particularly among older children. This suggests an interaction between developmental factors and musical structure in shaping expressive movement.

Upbeat melodies and imaginative songs elicited larger motor responses, particularly in older children. For the fourth metacarpal, the main effect for the song factor was statistically significant, and characteristic for "Yamanoongakuka," "Nabenabesokonuke," and "Genkotsuyamanotanuki" for 3-year-old, "Yamanoongakuka" for 4-year-old and 5-year-old, and "Kaerunouta" for 5-year-old.

The results showed that the total moving distance and the moving average acceleration tended to increase in response to upbeat melody were similar to the results of the analysis of the elements of body movement in musical expression.

These findings extend previous research by providing insights of micro level into finger motor dynamics. Importantly, they demonstrate that musical expression can be examined as a measurable motor phenomenon, bridging qualitative educational practice and quantitative analysis.

Limitations include the relatively short recording duration and the focus on a single cultural context. Future research should incorporate longitudinal designs, cross-cultural comparisons, and multimodal data integration such as eye tracking and machine learning approaches.

Despite these limitations, the present study demonstrates the feasibility and value of using wearable motion capture technology to investigate fine motor behavior during musical expression in early childhood.

5. Conclusion

This study demonstrates that finger motor control during musical expression exhibits clear developmental differentiation in early childhood. In particular, the fourth and fifth metacarpals play a role in expressive movement. The findings suggest that musical expression can be understood not only as a cognitive and emotional activity but also as a measurable motor phenomenon. The third metacarpal has been found to play a role in supporting finger movements and activating the movements forming images of the proximal and distal phalanges before and after it (Sano 2025). As shown in the results of the cluster analysis mentioned above, the fourth metacarpal was found to support movements that express finer rhythms and image movements. The fourth metacarpal contribute to fine rhythmic and expressive movement. Regarding the moving average acceleration in the fourth and fifth metatarsals, a significant increase in the moving average acceleration from 3-year-old to 5-year-old to upbeat melody was found. However, a distinctive change was also found in which the moving average acceleration increased with comprehension of the lyrics, even for nursery rhymes whose lyrics induce large movements in time with regular beats and rhythms. The fourth and fifth metacarpals show increased the moving average acceleration with age and musical engagement.

By providing objective indicators of movement, this study offers a foundation for data-based assessment in early childhood music education. Future work should expand this approach to more detailed analyses and broader contexts.

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Ethical Approval

This study was reviewed and approved by the research ethics committee of Tokoha University as the affiliation of the author (Approval Number: Kenso 23-24, Approval Date: March 2, 2024). The research methodology was explained in detail at the facilities, and informed consent was obtained through the submission of consent forms by the cooperating facilities, the parents of the participant children, and the person in charge of the participant facilities.

Disclosure of Interest

The author reports there are no competing interests to declare.

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