A study on locomotion characteristics according to the level of cardiorespiratory endurance in adolescents

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Abstract

This study aims to investigate the differences in locomotion characteristics according to cardiorespiratory endurance in adolescents. The subjects were 51 students in the third grade of middle school, divided into the EG group (excellent group) and NEG group (non-excellent group) according to the cardiorespiratory endurance level. This study investigates the differences in locomotion characteristics according to cardiorespiratory endurance in adolescents. We used a 20-shuttle-run for cardiorespiratory endurance level, and a 1-minute walking test was performed for each speed by applying a differential speed. Cardiorespiratory endurance variables were based on VO$_2$ Max, and locomotion variables were analyzed by spatial-temporal parameters and foot range of motion parameters. Regarding the locomotion spatial-temporal parameters, adolescents with excellent cardiorespiratory endurance showed a more regular pattern, while foot inversion showed a more abnormal pattern. In particular, when the locomotion speed was slow, these characteristics were more clearly distinguishable. Our results confirm the characteristics of locomotion according to the growth of adolescents and can mediate the difference in walking speed to use as a primary database for the locomotion of adolescents.

Introduction

Students who partake in physical activity can boost their cardiopulmonary, muscle, blood circulation, and bone health. In addition, physical activity also contributes to improved academic performance, cognitive skills, and general health and well-being$^1$. However, levels of physical activity are decreasing around the world, caused in part by the lockdowns surrounding the COVID-19 pandemic. Consequently, physical inactivity has increased significantly in all age groups$^{2,3,4}$. Physical inactivity negatively affects cardiorespiratory fitness in children and adolescents and can lead to metabolic syndrome$^{5,6}$, which can negatively affect cardiorespiratory fitness over time, particularly in adults and the elderly. A lack of physical activity when younger will make an individual more susceptible to metabolic disease later in life$^7$. Physically inactive adolescents were found to have low VO$_2$ Max, which is a representative cardiorespiratory fitness index$^{8,9,10}$. Methods for measuring cardiorespiratory endurance can be estimated using several tests and protocols, although the most widely used test is the 20 m shuttle run. This test can be used effectively in group settings, such as in schools, and is a component of FitnessGram, which is part of the United States health and fitness management system$^{11,12,13,14}$.

Low levels of cardiorespiratory endurance can affect locomotion (gait) characteristics in adolescents. In previous studies, lower peak knee extensor movements during locomotion were associated with a rapid decline in cardiorespiratory fitness (VO$_2$ Max) in physically inactive adolescents$^{15}$. Based on these results, biomechanical locomotion characteristics are the best means of predicting physical fitness and inactivity levels in adolescents$^{16,17,18}$. Locomotion can simultaneously be our most basic and most complex movement. An appropriate locomotion cycle, flexible joint movement, and muscle action must be organically coordinated for regular locomotion, while an optimized lower extremity movement pattern must be generated through constant energy consumption$^{19}$. Crucial for effective locomotion is a basic
level of fitness, which can prevent falls, fatigue, pain, instability, injury, and higher energy expenditure\textsuperscript{20,21}. In addition, high levels of cardiorespiratory fitness, lower extremity strength, balance, and reaction time were all associated with better locomotion\textsuperscript{22,23}. Therefore, it is clear that the characteristics of normal locomotion are closely associated with physical fitness.

\( \text{VO}_2 \text{Max} \) levels during locomotion in adolescents show a different pattern than in healthy adults, mainly because the structure and size of the body are different from those of adults since they are still in the growth stage. Studies have also shown that children under the age of ten and adolescents have lower \( \text{VO}_2 \text{Max} \) levels than adults. Furthermore, after analyzing the energy expenditure rates at stable and fast locomotion speeds in various age groups, adolescents showed higher energy expenditure rates than adults at any speed, implying that the locomotion efficiency of adolescents is lower than in adults\textsuperscript{24}. We hypothesize that the locomotion characteristics for each locomotion speed will be different depending on the level of cardiorespiratory endurance. Therefore, this study aims to find out how the locomotion characteristics of adolescents differ depending on their locomotion speed. The results will be based on \( \text{VO}_2 \text{Max} \) levels determined through the 20 m shuttle run.

**Results**

**Spatial-temporal parameters**

A repeated measures ANOVA was performed to verify the interaction effect of locomotion speed and cardiorespiratory endurance level on cadence, walking speed, normalized stride length, and step length, and the main effects of all three variables were found to be statistically significant (in order, \( F = 251.89, p < .001, F = 9488.43, p < .001, F = 1003.64, p < .001, F = 1030.72, p < .001 \), respectively). In addition, the interaction effects of cardiorespiratory endurance level and locomotion speed were also shown to be statistically significant (in order, \( F = 5.75, p < .01, F = 6.18, p < .01, F = 6.52, p < .01, F = 4.21, p < .05 \), respectively). There was no statistical difference in the mean value of locomotion speed between the groups. In the cadence, the EG showed 106.33 ± 2.50 times/min, 113.3 ± 2.13 times/min, and 122.1 ± 1.91 times/min at slow, normal, and fast speeds, respectively, while the NEG showed 98.2 ± 2.55 times/min, 108.8 ± 2.18 times/min, and 119.5 ± 1.95 times/min at slow, normal and fast speeds, respectively. For the walking speed, the EG showed 0.99 ± 0.01 m/s, 1.32 ± 0.01 m/s, and 1.66 ± 0.01 m/s in order of locomotion speed, while the NEG showed 0.96 ± 0.01 m/s, 1.28 ± 0.01 m/s, and 1.58 ± 0.01 m/s. For the normalized stride length, the EG showed 0.57 ± 0.01 m/height, 0.71 ± 0.01 m/height, and 0.82 ± 0.01 m/height in order of locomotion speed, while the NEG showed 0.59 ± 0.01 m/height, 0.71 ± 0.01 m/height, and 0.80 ± 0.01 m/height. The step length was 0.48 ± 0.01 m, 0.59 ± 0.01 m, and 0.69 ± 0.01 m in order of locomotion for the EG, and 0.52 ± 0.01 m, 0.62 ± 0.01 m, and 0.70 ± 0.01 m for the NEG. For the interaction effects of locomotion speed and cardiorespiratory endurance level for single support phase, double support phase, and time of toe-off, the main effects of all three variables were statistically significant (in order, \( F = 255.27, p < .001, F = 255.17, p < .001, F = 255.08, p < .001 \), respectively), as were the interaction effects of cardiorespiratory endurance level and locomotion speed (in order, \( F = \)
3.77, \( p < .05, F = 3.76, p < .05, F = 3.76, p < .05 \), respectively). The statistical difference between the mean difference by locomotion speed within the group and the mean value between groups in the single support phase for the EG was 38.3 ± 0.28%, 39.2 ± 0.20%, and 40.6 ± 0.23% at slow, normal, and fast speeds, respectively, while the NEG was 36.7 ± 0.28%, 38.2 ± 0.21%, and 39.5 ± 0.23%. For the double support phase, the EG was 23.5 ± 0.56%, 21.6 ± 0.41%, and 18.8 ± 0.46% in order of locomotion speed, while the NEG was 26.6 ± .57%, 23.6 ± 0.41%, and 21.0 ± 0.47%. The time of toe-off was 61.7 ± 0.28%, 60.8 ± 0.20%, and 59.4 ± 0.23% in order of locomotion, while the NEG was 63.3 ± 0.28%, 61.8 ± 0.21%, and 60.5 ± 0.23% (Fig. 1).

**Range of motion parameters**

The main effects of locomotion speed and cardiorespiratory endurance level on the range of motion of inversion/eversion, dorsi/plantar flexion, and adduction/abduction were statistically significant for all three variables (in order, \( F = 44.173, p < .001, F = 378.535, p < .001, F = 0.16, p < .001 \), respectively). However, the interaction effects of cardiorespiratory endurance level and locomotion speed were not statistically significant. The mean difference in locomotion speed within the group showed a significant difference (Fig. 2). However, statistical differences in mean values between groups were only found in the ROM of the inversion/eversion variable. In order, ROM of the inversion/eversion was \(-1.40 ± 0.24°, -1.97 ± 0.29°, and -2.40 ± 0.32°\) for the EG, while the NEG was \(-2.55 ± 0.24°, -3.19 ± 0.29°, and -3.64 ± 0.33°\). For the ROM of the dorsi/plantar flexion, the EG showed \(-6.64 ± 0.61°, -10.19 ± 0.72°, and -13.92 ± 0.71°\) in order of locomotion speed, while the NEG showed \(-7.10 ± 0.63°, -10.98 ± 0.73°, and -14.04 ± 0.73°\). The ROM of adduction/abduction was \(0.05 ± 0.11°, 0.28 ± 0.13°, 0.64 ± 0.15°\) in order of locomotion for the EG, while the NEG was \(0.16 ± 0.11°, 0.56 ± 0.13°, and 1.01 ± 0.15°\).

**Discussion**

This study specified the locomotion characteristics of a group of male third-grade students divided into groups by their cardiorespiratory endurance levels as estimated by a 20-m shuttle run. The 20-m shuttle run was developed in 1984 as a non-gas analytical test method and is the most widely used method of estimating cardiorespiratory endurance. In addition, it is used as the primary method of the United States’ student fitness measurement program (FitnessGram)\(^{33,34,35}\).

The locomotion characteristics show differences depending on age and gender. Males generally have faster locomotion speeds than females, and also have less cadence and longer stride length. The locomotion speed of children and the elderly is also slower than that of adults\(^{24,36}\). Many studies have reported on the relationship between physical fitness and spatial-temporal locomotion parameters\(^{37,38,39}\). In particular, this study’s critical keyword for cardiorespiratory endurance and locomotion variables is energy expenditure. In a related study, when performing locomotion at the same speed, adolescents had a higher \( \text{VO}_2 \text{ Max} \) than both adults and the elderly and also showed significantly greater energy expenditure at slower speeds than faster ones\(^{24,40}\). The fact that these results were found in adolescents who do not
have locomotion disorders, when compared with the elderly, shows that their method of locomotion is different from that of adults and the elderly.

By comparing the locomotion characteristics between the two groups divided by cardiorespiratory endurance level, all locomotion variables in this study were found to be statistically significant in the average difference according to the locomotion speed. Furthermore, when comparing the two groups, the single support phase, double support phase, and time of toe-off variables all showed significant differences for each locomotion speed. Likewise, the range of motion inversion/eversion variable showed significant differences between the groups at slow locomotion speed.

This study is unique in that it compares the locomotion characteristics of the two groups by applying a locomotion differential speed protocol based on cardiorespiratory endurance standards for adolescents. When walking speed, single support phase, double support phase, time of toe-off, and inversion/eversion ROM of the foot was compared with the results of using the differential speed, and the results between groups, the locomotion of adolescents show different characteristics depending on their cardiorespiratory endurance level. In particular, the locomotion of adolescents shows more distinct characteristics according to the locomotion speed. Therefore, this study's main conclusion is that adolescents' locomotion characteristics vary according to their level of physical strength, particularly cardiorespiratory endurance. At the same time, significant differences were also found during slow locomotion speed among the single support phase, double support phase, time of toe-off, and inversion/eversion variables.

Additionally, and again depending on cardiorespiratory endurance levels, walking speeds showed a statistically significant difference at fast speeds, consistent with the results of previous studies that showed a correlation between physical fitness level and walking speed at maximal speed. In particular, walking speed was shown to be strongly associated with muscle strength, agility, and dynamic balance, and strengthening these physical factors increased walking speed. The group standard of this study was the cardiorespiratory endurance level, and it was found that adolescents with better cardiorespiratory fitness had faster walking speeds. Also, unlike the locomotion cycle and range of motion, there was a group difference in walking speed at fast locomotion speed, so it was found that the fitness level of adolescents could be confirmed at fast locomotion speed.

The longer it takes for the single support phase to converge to 40%, the shorter the time that the double support phase converges to 20%, and the shorter the time of toe-off converges to 60%. The more efficiently managed energy expenditure is considered healthy for muscle, equilibrium, and neurological function. In addition, if the ROM of inversion/eversion is less than −7° or greater than −4°, then there are likely to be difficulties with muscle nerves and muscle coordination. Based on these locomotion characteristics study results, analyzing the results showed statistically significant differences between the groups; the EG group showed more standard locomotion characteristics in the single support phase, double support phase, and time of toe-off—trends that became more apparent as the locomotion speed increased.
However, the inversion/eversion of the foot was smaller than the standard range of motion in healthy adults in both groups, and both groups also showed a tendency for eversion during locomotion. In addition, the dorsi/plantar flexion of the foot was smaller than the standard range of motion in healthy adults, although the difference was not statistically significant. The reason for this is that adolescents are in their growing period, and have an imbalance in ligament and muscle length due to the rapid growth of their bones\textsuperscript{46}. In the locomotion cycle of adults, maximum eversion appears mid-stance. However, the relatively small eversion in the adolescents in this study showed that the agonist actions of the peroneus longus, peroneus brevis, extensor digitorum longus, and extensor hallucis longus were sufficient during locomotion. Also, it was thought that the agonist action of the tibialis posterior, tibialis anterior, flexor hallucis longus, and soleus was also not working properly\textsuperscript{47,48,49,50,51}. The reason for this is that the lower leg muscles lose flexibility and the hamstrings tighten as a result of the limited hip joint ROM in adolescents. This leads to an imbalance in the contraction of the lower leg muscles\textsuperscript{52,53,54,55,56,57}. In summary, when performing locomotion, there is an imbalance in muscle activity in the lower extremities due to a decrease in muscle flexibility during the growth phase. Consequently, the locomotion characteristics of adolescents have a lower level of coordination than adults, and they form inefficient locomotion characteristics of the lower extremities.

However, it should be noted that in this study, the adolescents with excellent cardiorespiratory endurance levels showed inversion characteristics at a slow locomotion speed, unlike the NEG. Also, single support, double support, and time of toe-off showed characteristics closer to normal. Previous studies show that adolescents in the growing phase maintain locomotion stability even though they do not show a normal pattern of locomotion characteristics compared with adults. In addition, it was shown that adolescents with good cardiorespiratory endurance performed a normal locomotion cycle similar to the locomotion characteristics of adults by controlling locomotion by central control of the neural networks of movement, despite the limitations in the ROM of the lower extremities due to growth. The results suggest that the higher the cardiorespiratory endurance level, the more pronounced this pattern\textsuperscript{58,59,60}. In addition, although physical changes in the lower extremities of adolescents in the growth period can negatively affect locomotion performance, locomotion control can maintain stability through central control and mitigate unstable performance\textsuperscript{61}. Moreover, the most statistically significant locomotion characteristics of adolescents according to cardiorespiratory endurance level were in line with previous similar studies. Compared to children, adults, and the elderly, growing adolescents showed more inefficient characteristics related to energy consumption when performing slow locomotion\textsuperscript{24,40}.

Among the variables in this study, cadence, normalized stride length, and step length did not show any differences between groups or when compared with the normal locomotion characteristics of adults; they appeared to belong to the out-of-the-standard category. In addition, the adduction/abduction range of motion showed a pattern similar to that of the normal adult range at all locomotion speeds. Therefore, this study found that adolescents with high cardiorespiratory endurance levels showed relatively normal characteristics in the locomotion cycle phase compared with adolescents with low cardiorespiratory
endurance levels. However, both groups tended to invert more during locomotion because their flexibility and coordination deteriorated with growth, although the EG showed a more pronounced tendency.

What is noteworthy here is that there was a clear difference between the groups at slow locomotion speeds, and the adolescents in the growing stage showed an inefficient pattern in terms of energy expenditure at slow locomotion compared to children, adults, and the elderly. In particular, our results showed that the locomotion characteristics differed at slow speeds depending on the cardiorespiratory endurance level. A clear difference, found only during fast locomotion, was that the locomotion characteristics of adolescents were more pronounced at the slow locomotion speed.

**Limitations**

One limitation of our study is that the locomotion speed of adolescents reflected the general speed of adults. In a follow-up study, if each adolescent's preferred speed is measured and reflected in the experiment, we will be able to obtain more detailed characteristics. In this study, VO\(_2\) Max 60ml/kg/min was used as the standard, and it is believed that a more in-depth analysis would have been possible if other physical attributes of the students were considered in addition to VO\(_2\) Max, were considered.

**Methods**

**Subjects**

The subjects consisted of 51 male students in the third grade. After performing a 20-m shuttle run, the subjects were divided into two groups based on multiple regression equation results. The first group (n = 26, mean ± SD: height = 168.2 ± 5.42 cm, body weight = 54.04 ± 6.39 kg, BMI = 19.1 ± 1.6 kg/m\(^2\)) consisted of students with excellent cardiorespiratory endurance (maximal oxygen uptake; > 60 ml/kg/min), while the second group (n = 25, mean ± SD: height = 174.8 ± 4.49 cm, body weight = 78.3 ± 10.97 kg, BMI = 25.9 ± 3.3 kg/m\(^2\)) consisted of students with poor cardiorespiratory endurance (maximal oxygen uptake; < 60 ml/kg/min). Recent studies have shown that the VO\(_2\) Max reference value of well-trained youth and elite soccer players is 60 ml /kg/min\(^{25-27}\). Therefore, for this study, we also used the reference value of 60ml/kg/min based on the distinction between the excellent group (EG) and the non-excellent group (NEG). All participants written informed consent was obtained from the legal guardians of all the study participants, thoroughly introducing themselves to the contents of the experiment. The study protocol was approved by the Institutional Review Board of Pukyong University (IRB_1041386-202012-HR-73-01) and conformed to the Declaration of Helsinki. Also, all experimental procedures were performed the same way as the previously verified physical fitness measurement protocol and were conducted under the supervision of the school.

**Devices**
We used a system consisting of a computer and software (MotionCore, JEIOS, Korea) and a data logger (shoe-type) Smart Balance® SB-1 (JEIOS, Korea) with inertial sensors\textsuperscript{28,29,30} (Fig. 3). Bluetooth equipment mounted on shoes would send and collect measurements from signal collection devices connected to a computer. The regional coordinate system of the inertial sensor sets the anterior-posterior direction as the X-axis, the mediolateral direction as the Y-axis, and the vertical direction as the Z-axis. The spatial-temporal parameters (cadence, walking speed, stride length, step length, single support phase, double support phase, time of toe-off, and range of motion parameters (range of movement (ROM) inversion/eversion, ROM dorsi/plantar flexion, and ROM adduction/abduction) were analyzed by processing the acceleration and angular velocity obtained from the inertial sensor devices. The shoe size was adjusted for each participant, and the locomotion characteristics were measured on a treadmill. Polar (Verity, Polar Electro, Malaysia) was used to measure the maximum heart rate for the cardiorespiratory endurance level regression equation, while height and weight were measured using an automatic device (DS-103M, Jenix, Korea).

**Measurements**

The study subjects performed static stretching and warm-up exercises before measurement, and a 20-m shuttle run test was performed immediately after measuring height and weight. After a 10-minute break, the locomotion test began. The locomotion characteristics test consisted of one minute of walking at a slow (3.2 km/h), normal (4 km/h), and fast speed (4.8 km/h). The decision was made by adjusting the previous/next speed by about 20\% based on the protocol of Kim et al.\textsuperscript{31}, with a locomotion capacity of 4 km/h as an average speed. The 20-m shuttle run recorded the best performance (until they feel they can't run anymore) with one measurement.

**Data analysis**

A total of 84 13-year-old adolescents were surveyed, although the subject group with a significant difference in giving up and positive values during the experiment was excluded from the analysis (51 adolescents). Repeated measurement variance analysis was used to verify the interaction effect of movement speed and cardiorespiratory endurance on the locomotion characteristics. The mobility characteristics were analyzed for spatial-temporal parameters (cadence, walking speed, stride length, step length, single support, double support, time of toe-off), and ROM of inversion/eversion, ROM of dorsi/plantar flexion, and ROM of adduction/abduction. Cardiorespiratory endurance, by contrast, was calculated using the multiple regression estimation equations [maximum oxygen intake = 6.473 - (12.331 × gender) - (0.805 × age) - (0.883 × height) - (1.167 × weight) - (0.052 × maximum heart rate) - (0.158 × time)] as shown by Akay et al.\textsuperscript{32}. The average value was used as the variable calculated on the mean of the left and right sides among the mobility characteristics. The data obtained at the slow, normal, and fast speeds were calculated and analyzed as average values. SPSS Version 26.0 (IBM Corp., Armonk, NY) was used to analyze the results, with a \textit{p}-value of < .05, denoting statistical significance.

**Conclusions**
This study identified differences in locomotion characteristics according to adolescents’ cardiorespiratory endurance levels during differential speed locomotion. Regarding the locomotion spatial-temporal parameters, adolescents with excellent cardiorespiratory endurance showed a more regular pattern, while foot inversion showed a more abnormal pattern. In particular, when the locomotion speed was slow, these characteristics were more clearly distinguishable. It should be noted that these locomotion characteristics have a negative effect on the inversion angle of the foot because of the reduced flexibility and coordination as the adolescent enters the growth phase. Nevertheless, we can conclude that the locomotion cycle of adolescents is relatively close to that of adults by central control of the neural networks of movement. Our results also confirm the characteristics of locomotion according to the growth of adolescents and can mediate the difference in walking speed to use as a primary database for the locomotion of adolescents. In addition, our differential speed locomotion intervention may inspire future studies to confirm the association between locomotion and fitness level.

Declarations

Data availability

All data used in this study is presented here and available in the supplementary material. Additional request may be made directly through the corresponding author on reasonable request.

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Author contributions

S.C: Conceptualization, Formal analyses, and data interpretation, Writing-Original Draft, Writing-Review & Editing; M.S.: Data processing, Data analysis, Writing-Sections of the manuscript; Y.L.: Data acquisition, Writing-Review & Editing; Y.S.: Conceptualization and Study Design, Writing-Review & Editing, Resources, Funding Acquisition J.J.: Supervision, Conceptualization and Study Design, Data interpretation, Writing-Review & Editing, Resources, Funding Acquisition.

Competing interests

The authors declare no competing interests.

References


**Figures**
Figure 1

Statistical results of locomotion speed RM ANOVA by group according to a cardiorespiratory endurance level of spatial-temporal parameters (A – G). Confidence Interval (Lower right).
Figure 2

Statistical results of locomotion speed RM ANOVA by group according to a cardiorespiratory endurance level of single ROM of inversion/eversion (A), ROM of dorsi/plantar flexion (B), and ROM of adduction/abduction (C). Confidence Interval (Lower right).
Inertial sensors are mounted on the data logger. The shoe-type data logger can continuously record locomotion data during walking. The data are then wirelessly transferred to the data processing device via Bluetooth.