Journal of Physical Education and Sport ® (JPES), Vol. 23 (issue 5), Art 161, pp. 1318 - 1324, May 2023
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Effects of maturation on walking pattern in early adolescent boys and girls

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Published online: May 31, 2023
(Accepted for publication May 15, 2023)
DOI:10.7752/jpes.2023.05161

Abstract
Normal gait development has been widely investigated due to the importance of locomotion for independent daily living. Understanding gait control and its process is fundamental, especially in critical developmental periods, for effective interventions. However, less is known about longitudinal changes in walking patterns between adolescent boys and girls, who experience an accelerated increase in both height and weight, causing low gross motor coordination. Here, to address this literature gap, we evaluated the effect of maturity and walking speed in Vertical Ground Reaction Forces (VGRF) and time gait parameters, in twenty-three boys (age 12.5 ± 0.29) and twenty-two girls (age 10.5 ± 0.32). They performed normal and fast pace at their self–selected speed, at 18 and 9 months before peak height velocity (PHV) and at PHV. We quantified the magnitudes of the three VGRF: first peak (Fzmax1), second peak (Fzmax2), and valley (Fzmin), along with total contact time (ts), and gait variability in anterior-posterior (AP) and mediolateral (ML) directions. A mixed model of repeated measure analysis of variance (RM ANOVA) revealed significant effects of maturity and walking speed in VGRF, ts, and variability. Girls exhibited a steadier walking pattern than boys, with lower Fzmax1 and ts, since variability decreased values near PHV for both sexes. In summary, gait is a still maturing process in early adolescents, significantly influenced by walking speed. Growth spurt affects in a different way gait patterns of adolescent boys and girls. The data from this study could be used as a reference for educators and trainers, planning adolescent interventions and preventing injuries.
Keywords: growth spurt, adolescents, maturity, walking speed

Introduction

Locomotion is a complex cyclical phenomenon, aiming to drive the center of mass stably in the desired direction. Since adolescents theoretically have a mature walking ability, sudden peripheral changes (e.g. height increase) seems to affect the performance of gait (Bisi and Stagni (2016). Therefore, understanding of the process of gait control during adolescence is fundamental for effective motor behaviour. Ground reaction forces (GRF) seem to be the representative measurement of gait, as they affect the acceleration of the body's center of mass (Masani et al., 2002). Additionally, time and variability parameters are useful for the interpretation of gait in growing children, mainly as walking speed changes.

Maturity of normal gait in children has been largely studied. However conflicting results exist about the age when gait parameters mature. Many researchers concluded that GRF mature by the age of 5 years old (Beck et al., 1981; Stansfield et al., 2001; Sutherland et al., 1988), while others reported changes till the age of 10 (Diop et al., 2005; Takegami, 1992) and 17 years old, with the effect of walking speed (Fukuchi et al., 2019). It is worth noting that children in most of the aforementioned investigations were allowed to walk in self-selected speeds. In the same way, time parameters, usually normalized to body size, continued to change up until the age of 16 years (Menkveld et al., 1988; Norlin et al., 1981). Changes in gait parameters were attributable to age, mostly till the age of 5 years old and to body size (weight, height, leg length) and normalized speed thereafter. Guelle et al. (2016) also concluded that gait is not totally mature before the age of 17 years old investigating gait variability, as a useful parameter to determine gait maturity (Gouelle et al., 2016). However, gait control around the age of PHV remains unknown.

Sex differences during walking are generally acknowledged in cross sectional studies, mainly executed in adults. Gait parameters, joint kinematics, kinetics and electromyographic parameters, seem to be different between preadolescents and adult females and males (Di Nardo et al., 2017). In this study, authors reported differences between boys and girls with girls exhibit a more mature gait pattern than boys, similar to young adults. Authors recognized adolescence as the time where gait is completing maturation. Additionally Dufek et al. (2012) referred adolescent boys to display a less consistent walking pattern than girls (Dufek et al., 2012). Moreover, different body variables between early adolescent boys and girls, opposite to adults, seemed to affect walking to running transition speed, in a recent study, with authors emphasizing the importance of adolescent

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maturation in gait pattern modulation (Đurić et al., 2022). In contrast, Moreno-Hernantez at al. (2010) did not find gender differences in spatiotemporal gait parameters in children 6-13 years old (Moreno-Hernández et al., 2010). Therefore sex differences in gait parameters of early adolescents need further investigation.

Longitudinal and cross-sectional studies in maturity of gait control of growing children came in controversy results. Therefore, the aim of the present longitudinal study was to identify time and variability gait parameters, along with vertical ground reaction forces, among healthy early adolescent boys and girls, walking at two different speeds, providing valuable data in the study of gait maturity during the critical period of growth spurt. We hypothesized that: 1.early adolescent girls would provide a more consistent gait pattern and 2.all the subjects would improve gait variability with age.

Material and methods

Participants

Twenty-three boys (age 12.5 ± 0.29) and twenty-two girls (age 10.5 ± 0.32) participated in this study. This age difference between boys and girls is consistent with the robust finding that PHV takes place two years earlier in girls, than boys, starting at about 10 ½ years of age (Tanner, 1981). Therefore, for each participant, we estimated the maturity offset (time relative to PHV) using a sex-specific multiple regression equation that is based on body mass, standing and sitting height, lower limb length, and chronological age (Mirwald et al., 2002). The equation, used extensively in the adolescent literature, is a reliable way to quantify biological maturity (Gebel et al., 2019). Participants' characteristics are summarized in Table 1. None of the participants had any previous musculoskeletal injuries. Parents or guardians signed a consent form as required by the Educational Policy Institute (ERC-009/2020) of the Aristotle University, which fulfills the ethical principles of the declaration of Helsinki.

Walking measurements

Prior to performing the walking test, participants performed a 10-min warm-up session that included jogging and lower-limb stretching exercises. Then subjects took two trials for familiarization. Right after, children walked barefoot at their self–determined normal and fast pace on an elastic 5-meter long corridor, passing with their right leg stepping on the kistler platform. Mean walking speed was 0.99-1.04 meters per second (m/s) for the normal pace and 1.05-1.25 m/s for the fast pace, with no significant differences between boys and girls. Force signals were transferred into a built-in 8-channel charge amplifier (Kistler 9281CA, 5233A2, output range: ±5V) with built in filter bridges (frequency response>7 kHz) and digitally sampled through an A/D card (1000 Hz). Three ground reaction forces on the vertical plane during the stance period of a walking cycle were evaluated: 1. magnitudes of first peak (weight acceptance) (Fzmax1), 2.second peak (push off) (Fzmax2) and 3.valley (mid-stance) (Fzmin) in both normal and fast pace. Reaction forces were normalized to body mass. Additionally total contact time (ts), was evaluated. Time parameter was normalized to body height. Variability (std/avg) in anterior-posterior (Ay) and medio-lateral (Ax) directions of both normal and fast pace was calculated. Force plate was connected via charge amplifiers to a laptop and data were acquired via Bioware software (Kistler) at a sampling rate of 1000 Hz. Data analyses from force plate was performed using specific routines written in Matlab (MathWorks, Inc.).

Statistical analysis

The data were analyzed using SPSS 26.0 Statistical Package (SPSS Inc, Chicago, IL). We performed a mixed model repeated measure analysis of variance (RM ANOVA) to determine the interactive effects of sex (males vs. females), task difficulty (normal pace, fast pace), and maturity (18 months before PHV, 9 months before PHV, at PHV) for the Fzmax1, Fzmin, Fzmax2, total contact time and variability (dependent variables). The level of significance was set at $p<0.05$ followed with appropriate corrections for multiple comparisons and post hoc tests. Data are presented as means ± standard deviations in text and tables and as means ± standard errors in the figures.

Results

Here, we examined the interactive effect of self-selected walking speed with maturity in early adolescents, boys and girls. We evaluated vertical ground reaction forces, normalized to body mass and time parameter, normalized to body height.

Table 1. Anthropometric measurements of adolescent boys and girls at three different times.

	Time	18 months prior to PHV	9 months prior to PHV	At PHV
BOYS (N=23)	Age (years)	12.5±0.3	13.1±0.2	13.7±0.5
	Body mass (kg)	48.9±11.6	53.3±11.9	57.7±13.1
	Height (cm)	155.7±7.3	160.9±7,5	165±7.1
	Maturity stage	- 18.0±7.2	- 9.0±7.2	- 3.6±8.4
GIRLS (N=22)	Age (years)	10.5±0.3	11.1±0.3	11.7±0.2
	Body mass (kg)	35.8±6.8	38.7±7.5	41.8±7.9
	Height (cm)	144±5.8	148.5±5.6	152.9±4.9
	Maturity stage	-16.8±4.8	-8.4±6.0	-2.4±4.8

Vertical Ground Reaction Forces-sex differences

We compared VGRF of adolescent boys and girls (Sex), during two different self-selected walking speeds (normal vs fast pace=Task Difficulty) at three time points (Maturity; 18 months prior to PHV; 9 months prior to PHV; at PHV). Main effect of maturity ($F_{2, 80}$ =3.3; p=0.041) and difficulty ($F_{1, 40}$=113.3; p=0.000) in Fzmax1 indicated that both growth spurt and walking speed affected first maximum GRF. There was a significant Sex x Maturity interaction ($F_{2, 80}$ =3.23; p=0.045), indicating that boys decreased Fzmax1 near PHV while girls exhibited similar values and sex difference occur mainly18 months prior PHV (Figure 1). An almost significant difficulty X sex ($F_{1, 40}$=3.9; p=0.053) interaction indicated an increased value for boys compared to girls, mainly for the difficult (fast pace) gait (Figure 2). The main effect for difficulty in Fzmax2 was significant ($F_{1, 40}$=85; p=0.000), indicating that all participants exhibited greater second peak for the fast pace. On the contrary, the main effect for difficulty ($F_{1, 40}$=106; p=0.000) and maturity ($F_{2, 80}$=42.5; p=0.000) for the mid stance (Fmin) was significant indicating that all participants decreased values for the fast pace, although increased values near PHV. Therefore, walking speed affect VGRF, with Fzmax1 and Fzmax2 increase values in fast pace, while Fmin decrease values. Maturity affect only Fzmax1 and Fmin, while sex differences exist only in Fzmax1. The remaining main effects and interaction terms were not significant (p>0.1).

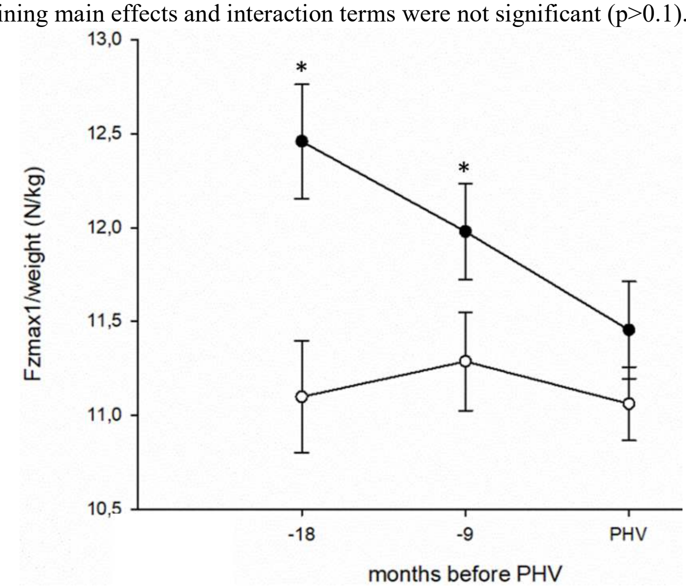

Figure 1. Maturity affects Fzmax1, with boys (black circle) display greater force than girls (white circle) mainly 18 and 9 months prior PHV.

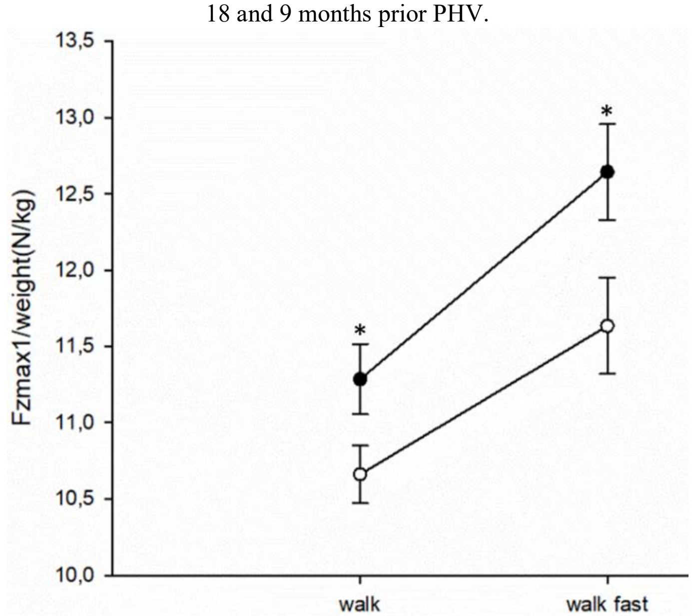

Figure 2. Walking speed affects Fzmax1, with boys (black circle) display higher values than girls (white circle).

Time parameters-sex differences

We compared time parameters during two different self-selected walking speed (difficulty), between early adolescent boys and girls (sex), in three different time points before and in PHV (maturity).

The main effect for maturity ($F_{2,\ 80}$ =30.6; p=0.000) and difficulty ($F_{1,\ 40}$=454.7; p=0.000) was significant in total contact time (ts), normalized to body height (s/cm), indicating that all participants decreased values near PHV mostly in the fast pace. Maturity X sex interaction ($F_{2,\ 80}$ =4.8; p=0.010) indicated lower contact time for girls compared to boys near PHV (Figure 3).

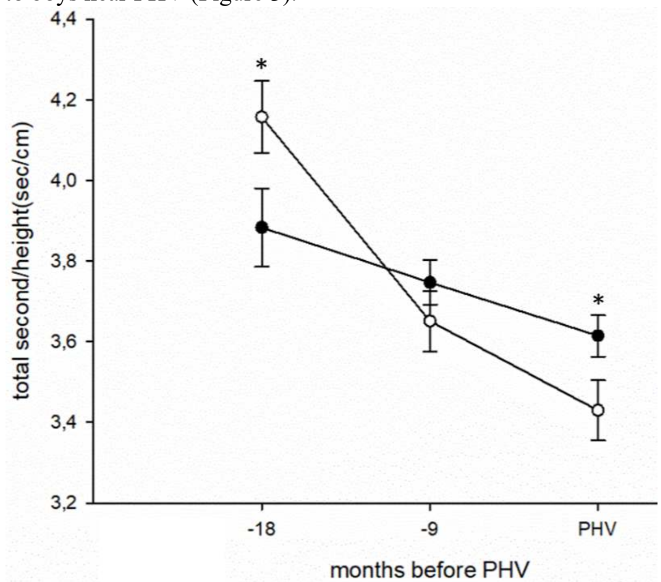

Figure 3. Maturity affects contact time, with boys (black circle) display higher values than girls (white circle) near PHV.

Main effect for maturity in variability in mediolateral (Ax) direction was significant ($F_{2,\ 80}$ =18.5; p=0.000), indicating decreased values for all participants near PHV (Figure 4). The remaining main effects and interaction terms were not significant (p>0.1).

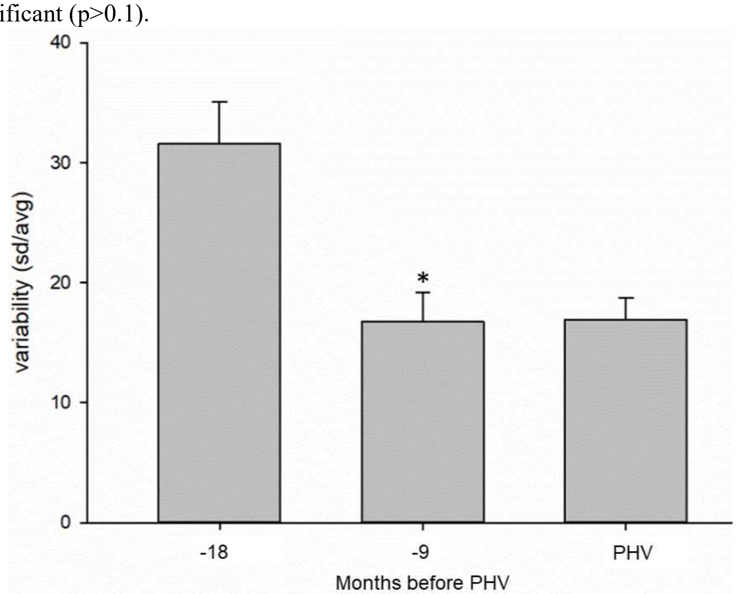

Figure 4. Maturity affects variability, with decreased values mainly after 9 months before PHV.

Discussion

The overall purpose of the study was to examine the effects of maturity and walking speed on gait characteristics of early adolescents, for the duration of 18 months before, till the age of PHV, concerning to sex differences. Main findings were: 1.Both maturity and walking speed affected first maximum vertical GRF (Fzmax1), with decreased values near PHV and increased values for the fast pace. Additionally, boys exhibited greater Fzmax1 than girls, mainly 18 months prior PHV and for the fast pace. 2. On the contrary only walking speed affected second peak (Fzmax2), with values increased for the fast pace similarly for boys and girls. 3. Maturity and walking speed affected Fzmin, with increased values near PHV and decreased values for the fast pace for both sexes. 4. Total contact time was affected by maturity, walking speed and sex, with lower values near PHV and with girls exhibiting lower values than boys near PHV. 5. Maturity affected variability, with decreased values near PHV for both sexes.

Vertical Ground Reaction Forces

In our study walking speed affected the three of vertical GRF, with different contribution between boys and girls only for the first maximum peak (Fzmax1). These findings are in agreement with Beck et al. (1981) showing that heel strike (Fzmax1) and toe-off (Fzmax2) increased and mid-stance (Fzmin) decreased with increasing speed in children and adolescents 1-14 years old (Beck et al., 1981). The above alterations result from the increased upward and downward acceleration of the center of mass during walking at a higher speed. To similar results came Linden et al. (2002) in decreased walking speed of 8-11 years old children (van der Linden et al., 2002). On the contrary Stansfield et al. (2001; 2006) in a 7 years longitudinal study in 5years old children, referred no effects of walking speed in Fzmax2, concluding that gait control was achieved primarily in early to mid-stance and there was no need to modulate the vertical GRF to provide the required horizontal acceleration by late stance (Stansfield et al., 2001) and that second peak was mostly associated with body's control of stability than maintenance of speed (Stansfield et al., 2006). Since aforementioned longitudinal studies included children up to 12 years old, we assumed that age must be the explanation for this discrepancy, so authors failed to find influences of accelerated increases in both height and weight in gait patterns, happening later in early adolescents. Thus, it seems that growth spurt affected body control stability in early adolescents in our study, with obvious changes in second peak with increasing walking speed. On the other side we found that maturity affected Fzmax1 and Fmin but not Fzmax2, with sex interaction observed only for Fzmax1. Previous studies in children up to 12 years old came to the conclusion that vertical GRF didn't change with age after the age of 5-8 (Beck et al., 1981; Diop et al., 2005; Stansfield et al., 2001). However Beck et al. referred changes in gait patterns of children 4-14 years old correlated to growth, when retesting them after more than three months period (Beck et al., 1981). It seems that longitudinal data in early adolescents highlights more clearly gait patterns differences. This is the first study feature longitudinal changes in VGRF in adolescents before PHV.

Time parameters

We normalized time parameters to body height, as it has been suggested, in order to evaluate whether changes in gait parameters were only a function of changes in biomechanics related to growth (Hausdorff et al., 1999). We found that total contact time (ts) decreased values near PHV and was shorter for the fast pace. Beck et al. (1981) in a cross-sectional study to 1-14 years old children, found that time of support decreased with increasing walking speed and changed with age due to changes in height (Beck et al., 1981). Other authors reported increased stance duration with age in young children due to maturation of balance centers, allowing longer support phase (Diop et al., 2005; Viel, 2000) but no further changes after 10 years old (Hillman et al., 2009; Norlin et al., 1981). It seems that as children grow older lower contact time, especially for faster pace, its evidence of a more mature and economical gait pattern. Gait variability seems to be another strong indicator of mature gait patterns. We found that gait variability decreased significantly near PHV in mediolateral direction, for both sexes similarly. These results are in agreement with previous findings, indicating that mature walking is a gradual process which develops through adolescence (Kung et al., 2019) with gait variability decrease as children get older and mature walking emerged between 13-14 years (Gouelle et al., 2016; Scafetta et al., 2009). Interestingly, Bisi & Stagni (2016) in a cross-sectional study, found higher gait variability in more mature 15 years old male adolescents, compared to less growing peers of the same age, during walking in dual task but not in single task (Bisi & Stagni, 2016). Given the aspects described above, complexity can affect gait pattern, resulting in a less steady walking performance in growing male adolescents. Future longitudinal studies should investigate sex differences in complexity influences adolescent walking parameters.

Sex differences

We found that maturation and walking speed affected in a different way first peak of vertical GRF (Fzmax1) between boys and girls, with girls displaying lower values than boys mainly 18 months prior PHV and for the fast pace. An explanation for this, is that increased Fzmax1 represents an increased demand on lower limb muscles as they work eccentrically to reverse downward moments after initial heel contact (White et al., 1996). It seems that boys, in order to maintain balance on the platform, especially for the fast pace, increased their heel contact more than girls did, causing an increased effort in lower limb muscles. It's of worth noticed, a higher first peak, compared with the second peak, for boys only and for both normal and fast pace. Linden et al. (2002) explained this phenomenon as a "crashing down" onto the "good" leg, resulting from decreased control or weakness of the opposite leg (van der Linden et al., 2002). Additionally we found that total contact time was lower for girls than boys, mainly near PHV, for normal and fast pace similarly. Dufek & Currie (2012) agreed with these findings, suggesting that males produced a less consistent walking pattern than females, due to a different gait control in adolescence (Dufek et al., 2012). Other previous cross-sectional studies failed to find sex differences in electromyographic (Di Nardo et al., 2017) and spatiotemporal gait parameters (Gouelle et al., 2016; Norlin et al., 1981) in children and adolescents. However Nardo et al. (2017) referred sex differences in EMG parameters for ankle muscles that started to occur in the beginning of adolescence and was acknowledged in adults (Di Nardo et al., 2017). It is likely that the neuromuscular adaptations which occur during early adolescence, particularly in lower limbs, influence gait control, indicating more mature patterns for girls than boys.

Conclusion

Results of this investigation have identified the effects of walking speed, maturation and sex in early adolescent gait patterns with girls exhibiting a more mature manifestation of walking than boys. This conclusion is based on the findings that girls exhibited lower values of first peak (Fzmax1) of vertical GRF and lower contact time than boys, mainly in fast pace, in the process of growth spurt. Both sexes reduced gait variability near PHV. Since walking is theoretically a well-achieved fundamental skill in adolescence, growth spurt and walking speed seem to affect the performance of gait, in a different way for boys and girls. These findings provide a basic understanding of gait control in a critical time of motor development. Our results could be important to teachers, coaches and researchers in way to adapt practical tasks related to maturity status and sex.

Conflict of Interest

The authors have no conflicts of interest to disclose

References

Beck, R., Andriacchi, T., Kuo, K., Fermier, R., & Galante, J. (1981). Changes in the gait patterns of growing children. *JBJS*, *63*(9), 1452-1457.

Bisi, M. C., & Stagni, R. (2016). Development of gait motor control: what happens after a sudden increase in height during adolescence? *Biomedical engineering online*, *15*(1), 1-12.

Di Nardo, F., Laureati, G., Strazza, A., Mengarelli, A., Burattini, L., Agostini, V., . . . Fioretti, S. (2017). Is child walking conditioned by gender? Surface EMG patterns in female and male children. *Gait & posture*, *53*, 254-259.

Diop, M., Rahmani, A., Belli, A., Gautheron, V., Geyssant, A., & Cottalorda, J. (2005). Influence of speed variation and age on ground reaction forces and stride parameters of children's normal gait. *International journal of sports medicine*, *26*(08), 682-687.

Dufek, J. S., Currie, R. L., Gouws, P.-L., Candela, L., Gutierrez, A. P., Mercer, J. A., & Putney, L. G. (2012). Effects of overweight and obesity on walking characteristics in adolescents. *Human movement science*, *31*(4), 897-906.

Đurić, D., Dobrijević, S., Kojić, F., Ranisavljev, I., Đurić, S., & Ilić, V. (2022). Body morphology and gait transition of adolescents: A comprehensive approach. *Anthropological Notebooks*, *28*(1), 42-57.

Fukuchi, C. A., Fukuchi, R. K., & Duarte, M. (2019). Effects of walking speed on gait biomechanics in healthy participants: a systematic review and meta-analysis. *Systematic reviews*, *8*(1), 1-11.

Gebel, A., Lüder, B., & Granacher, U. (2019). Effects of increasing balance task difficulty on postural sway and muscle activity in healthy adolescents. *Frontiers in physiology*, *10*, 1135.

Gouelle, A., Leroux, J., Bredin, J., & Mégrot, F. (2016). Changes in gait variability from first steps to adulthood: normative data for the gait variability index. *Journal of motor behavior*, *48*(3), 249-255.

Hausdorff, J., Zemany, L., Peng, C.-K., & Goldberger, A. (1999). Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. *Journal of applied physiology*, *86*(3), 1040-1047.

Hillman, S. J., Stansfield, B. W., Richardson, A. M., & Robb, J. E. (2009). Development of temporal and distance parameters of gait in normal children. *Gait & posture*, *29*(1), 81-85.

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2019). Age-dependent variability in spatiotemporal gait parameters and the walk-to-run transition. *Human movement science*, *66*, 600-606.

Masani, K., Kouzaki, M., & Fukunaga, T. (2002). Variability of ground reaction forces during treadmill walking. *Journal of applied physiology*, *92*(5), 1885-1890.

Menkveld, S. R., Knipstein, E. A., & Quinn, J. R. (1988). Analysis of gait patterns in normal school-aged children. *Journal of pediatric orthopedics*, *8*(3), 263-267.

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine and science in sports and exercise*, *34*(4), 689-694.

Moreno-Hernández, A., Rodríguez-Reyes, G., Quiñones-Urióstegui, I., Núñez-Carrera, L., & Pérez-SanPablo, A. I. (2010). Temporal and spatial gait parameters analysis in non-pathological Mexican children. *Gait & posture*, *32*(1), 78-81.

Norlin, R., Odenrick, P., & Sandlund, B. (1981). Development of gait in the normal child. *Journal of pediatric orthopedics*, *1*(3), 261-266.

Scafetta, N., Marchi, D., & West, B. J. (2009). Understanding the complexity of human gait dynamics. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *19*(2), 026108.

Stansfield, B., Hillman, S., Hazlewood, M., & Robb, J. (2006). Regression analysis of gait parameters with speed in normal children walking at self-selected speeds. *Gait & posture*, *23*(3), 288-294.

Stansfield, B. W., Hillman, S. J., Hazlewood, M. E., Lawson, A. A., Mann, A. M., Loudon, I. R., & Robb, J. E. (2001). Sagittal joint kinematics, moments, and powers are predominantly characterized by speed of progression, not age, in normal children. *Journal of Pediatric Orthopaedics*, *21*(3), 403-411.

Sutherland, D., Olshen, R., & Biden, E. (1988). *The development of mature walking*. Cambridge University Press.

Takegami, Y. (1992). Wave pattern of ground reaction force of growing children. *Journal of pediatric orthopedics*, *12*(4), 522-526.

Tanner, J. M. (1981). Growth and maturation during adolescence. *Nutr Rev*, *39*(2), 43-55.

van der Linden, M. L., Kerr, A. M., Hazlewood, M. E., Hillman, S. J., & Robb, J. E. (2002). Kinematic and kinetic gait characteristics of normal children walking at a range of clinically relevant speeds. *Journal of Pediatric Orthopaedics*, *22*(6), 800-806.

Viel, E. (2000). *La marche humaine, la course et le saut: biomécanique, explorations, normes et dysfonctionnements* (Vol. 9). Elsevier Masson.

White, S., Tucker, C., & Lifeso, R. (1996). Verbal feedback cues for altering vertical ground reaction forces patterns in gait re-education training. *Gait & posture*, *2*(4), 206.