



Original research

Biomechanical correlates of running performance in active children

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ABSTRACT

Objectives: Examine the running kinematics in healthy, physically active prepubescent children and to determine if specific biomechanical factors correlate with running performance.

Design: Cross-sectional study.

Methods: Fifteen children (age 9 years, ± 11 months) completed a 1 km time trial before undergoing three-dimensional running motion analysis.

Results: A strong positive correlation was observed between the biomechanical variables of stride length ($p < .01$), contact time ($p < .01$) and ankle dorsiflexion angle ($p = .04$) with time trial performance. Between variable analyses revealed a strong positive correlation between peak angles of hip adduction and knee flexion. There was no correlation between hip adduction and knee flexion peak angles or the vertical displacement of centre of mass with trial performance.

Conclusions: The results of this study show that children with a better time trial performance display longer stride length, shorter contact time and mid or forefoot strike pattern. These findings have implications for targeted technique intervention in children's running training to improve running performance.

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1. Introduction

Running is a fundamental motor skill that forms the basis of many individual and team sports, games and pursuits.¹ Children typically develop an initial immature running movement pattern from approximately 18 months of age² with maturity usually achieved by 4–6 years of age, while the development of specific expertise in running is likely to require 10 years or 10,000 h of deliberate practice.³ A retrospective analysis of the fundamental motor skills of over 27,000 Australian children aged 6–12 years, spanning the past 30 years to 2012, clearly demonstrates a significant decline in Australian children's performance of fundamental motor skills.⁴ Given that participating in well-structured and appropriately scheduled practice is the most critical factor in developing expertise in fundamental motor skills such as running⁵; it is likely that a decline in primary school aged children's participation in organized sport and physical activity is responsible for their decline in fundamental motor skill performance. The lack of expertise in fundamental motor skills in today's children could potentially impact upon future generations because observing others perform motor skills is critical to learning how to perform motor skills

oneself.⁶ Considering the length of time and investment required to develop expertise in a motor skill, arresting future declines in the general population's ability to perform fundamental motor skills necessitates intervention immediately.

Developing sport specific skills is considered to be a key contributing factor to achieving successful participation in a chosen sport.¹ Research examining the hierarchy of motor skills supports the contention that the development of fundamental motor skills such as running should occur in early childhood prior to the development of sport specific skills in adolescence.⁷ Children who demonstrate poor running skill have been found to be less physically active and have a higher standardized Body Mass Index (BMI) in comparison to those who perform the skill well.⁸ Further, children with poor running skill continue to be less active into adolescence compared to their more skilled counterparts.⁷ In Australia, there are more than 716,000 children between the ages of 5 and 14 who are either overweight or obese. This estimate can be aligned to recent USA work by Finkelstein et al.,⁹ who estimated the added cost of lifelong health care for each individual overweight or obese child to be US\$19,000 per child. This is in contrast to the estimated US\$12,900 per child if the child maintains a healthy weight but becomes overweight or obese in adulthood. Thus, well designed running training programs have the potential to not only target physical activity levels in childhood, but also promote physically active adolescents and adults by giving them the necessary, fun-

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damental running skill to participate in many sports, games and physical pursuits throughout their lifespan

Accurate feedback during instruction is important to both facilitate learning and prevent injuries that arise from poor technique.¹⁰ Thus, a thorough understanding of the biomechanics of running in children is critical to the design of effective running training programs targeting children. The biomechanical factors that contribute to running in adults are well known and include: optimal stride length^{11,12} contact time,¹¹ frontal plane hip stability,¹³ greater knee flexion during swing,¹¹ and low vertical displacement of center of mass (COM).¹² These factors have been linked to running skill and economy due to their role in maximising efficiency of force distribution and energy use.¹⁴ Research also indicates a relationship between knee and ankle joint angles at heel-strike, and the attenuation of impact.^{15,16} Poor attenuation of impact may increase energy expenditure during running, affecting running economy and performance.^{15,17} Additionally, abnormal or excessive soft tissue loading is associated with overuse injury.^{15,18} Abnormal biomechanics such as excessive rear foot eversion and altered impact forces during stance phase¹⁹ have been linked with an increased risk of running-related injury. Most importantly, all these factors are modifiable in adult runners, with targeted gait retraining proposed as a potential avenue for skill improvement and the prevention of injury.¹⁹

Compared to studies in adults, there is a lack of research examining the biomechanics of running in children with a developmentally mature running pattern. Studies have examined the differences between the kinematics of children with Developmental Coordination Disorder (DCD) and healthy controls^{12,20} and although comparative differences have been reported, a specific description of whether a normative running style exists in healthy children and how this may relate to running performance is lacking. Consequently, an understanding of the modifiable biomechanical components of running gait in children do not exist.¹⁸ Thus, the design of running training programs for children are based on inferences drawn from adult running data which may have implications to injury risk and poor transfer of learning from suboptimal training methods.¹⁹

Therefore, the aim of this study was to collect biomechanical data of running in typically developing, physically active, prepubescent children and to investigate whether specific biomechanical factors correlate with running performance. Any knowledge gained may guide the implementation of more directed running training programs for children in the future, which may in turn assist in enhancing running performance and decreasing the risk of overuse injury.

2. Methods

A convenience sample of fifteen healthy prepubescent children (nine male) were recruited through word of mouth from local community-based sporting groups and primary schools. Participants were all involved in organized running based sports for a minimum of 1 year prior to the study, with the specific frequency, intensity and level of activity screened for using an initial questionnaire. Children were excluded if they had an existing musculoskeletal injury or medical condition likely to affect their running performance, or were post-pubescent as determined by their parent/guardian according to the sexual maturation scale.²¹ Informed written consent to participate in a protocol approved by a University Human Research Ethics Committee was obtained from each participant's parent/guardian. Verbal assent was obtained from each child prior to participation and confirmed repeatedly during data collection.

Participants attended two separate data collection sessions with a minimum of three day between sessions. On the first occasion, participants completed a 1 km time trial consisting of two and a half laps of a marked 400 m grass athletic track. Participants completed the time trial in their normal running attire and footwear and were instructed to run at the time trial as a race to get the quickest time. Finishing time was manually recorded using a stop-watch and participants were given verbal encouragement every 200 m throughout the trial. Prior to commencing the time trial participants were familiarised to the course then guided through a running specific warm-up routine. All time trials were performed during the morning to ensure similar environmental conditions for all participants.

On the second occasion, participants underwent three dimensional analysis of their running gait. Anthropomorphic data including height and weight were collected prior to commencing the analysis. Fourteen millimeter retro-reflective markers were then affixed to the lumbar spine, pelvis, hip, femur, tibiofemoral joint, ankle and foot as specified by Besier et al.²² The experimental task consisted of a set of 30 m runs through a motion analysis laboratory at a speed equivalent to each participant's average speed during the 1 km time trial. Each 30 m run trial comprised of a 10 m run up to the laboratory, 10 m inside the laboratory and a further 10 m follow through on the other side of the laboratory. Running kinematics were assessed using an 18 camera, high speed motion capture system (Vicon[®] MX, Oxford Metrics, Oxford, UK) sampling at 250 Hz. Participants completed three familiarisation trials to practice running through the laboratory at the specified speed followed by a minimum of three successful experimental trials. A trial was considered successful if the participant's time to transverse a set of point-to-point timing gates placed at the entry and exit of the laboratory was within a range of ± 0.25 s of their calculated average time to traverse 10 m in the 1 km time trial. Participants completed the experimental task in their normal running shoes.

Captured kinematic data was processed in manufacturer-supplied software (Vicon Nexus, 1.8.5). The kinematic data was filtered using a fourth-order zero phase shift Butterworth digital low-pass filter, whereby the optimal cut off frequency (14 Hz) was determined using residual analysis. A three dimensional model of the lower limb was created using a custom written LabVIEW program (LabVIEW v2011 SP1: National Instruments, Austin, Tx), based on each participant's static calibration trial and inertial properties.²³ Each running trial was temporally normalised to 101 data points where a complete gait cycle was defined from foot contact to foot contact of the same limb.

The average of three trials was used in motion analysis to ensure typical running pattern measurements could be achieved. Key kinematic variables were identified throughout the gait cycle and a Pearson's correlation was performed to determine whether these had an association with time trial performance. Statistical analysis was conducted using SPSS (version 20).

3. Results

Participants had a mean of 3.43 years (SD 1.49) running experience, and were training a mean of 4.14 h per week (SD 2.90). There were no statistically significant differences between data from male and female participants in this study, further participant characteristics are shown in Table 1. The correlations between time trial performance and running kinematics and between measures of running kinematics is shown in Table 2. Fig. 1 presents the kinematics of the hip, knee and ankle joint in the sagittal, frontal and transverse planes during one complete gait cycle (foot strike to foot strike). Inspection of the graphical representations of the relationship between the children's running kinematics and their

Table 1
Participant characteristics. No statistically significant difference in characteristics between male and female participants $p > .05$.

Variable	Mean (SD) n = 15	Male Mean (SD) n = 9	Female Mean (SD) n = 6
Age (years)	9.95 (1.35)	9.47 (1.48)	10.50 (0.73)
Height (cm)	143.07 (7.35)	142.6 (9.38)	143.67 (3.14)
Body mass (kg)	34.38 (4.03)	33.90 (3.95)	35.10 (4.41)
Body mass Index (kg/m ²)	16.83 (1.94)	16.73 (2.13)	16.98 (1.80)
Time trial time (min)	4.86 (0.65)	4.70 (0.71)	5.21 (0.41)

Table 2
Mean and standard deviation for variables analysed in cohort.

Variable	Mean (SD)	Correlation with Time r (13)
Time (min)	4.86 (0.65)	
Stride length (m)	2.39 (0.32)*	$r = -0.81, p < .01^*$
Contact time (% gait cycle in stance)	31.14 (2.89)*	$r = 0.75, p < .01^*$
Ankle DF angle at foot strike (deg)	5.99 (9.89)#	$r = 0.56, p = .04^{\#}$
Hip adduction peak (deg)	13.00 (2.15)	$r = -0.25, p = .40$
Knee flexion peak (deg)	39.14 (15.13)	$r = -0.24, p = .42$
COM vertical displacement (m)	0.10 (0.02)	$r = 0.25, p = .40$

* Indicates significance at $p < .01$ level.
Indicates significance at $p < .05$ level.

running performance suggested that stride length (Fig. 2 – see Supplementary material), contact time (Fig. 3 – see Supplementary material) and ankle dorsiflexion angle at foot strike (Fig. 4 – see Supplementary material) were all related to time trial performance. Pearson’s correlations revealed that a faster time trial was very strongly correlated with a longer stride length [$r(13) = -0.812, p < .001$]. Visual inspection of the scatterplot suggested a non-linear relationship between stride-length and time. Curve estimation suggested a marginally closer fit for a quadratic as opposed to a linear regression equation to represent the relationship between

stride length and time and this equation suggested an optimal stride length of 2.66 m [Quadratic: $r^2(13) = .717$, Adjusted $r^2(13) = .666, F(2,13) = 13.96, p = .001$; Linear: $r^2(13) = .660$, Adjusted $r^2(13) = .631, F(2,13) = 23.26, p < .001$].

Pearson’s correlations also revealed that a faster time trial was strongly correlated with a shorter contact time [$r(13) = .753, p = .002$], and a smaller dorsiflexion angle [$r(13) = .559, p = .04$]. The graphical representation of the children’s dorsiflexion angle at foot strike suggested two distinct landing patterns with eight of the children landing in dorsiflexion ($M = 13.87^\circ, SD = 3.34^\circ$) and six in plantarflexion ($M = 4.50^\circ, SD = 2.70^\circ$). Consequently follow-up one-way ANOVAs were performed with landing position (rearfoot vs mid-to-forefoot) as a grouping variable to determine whether the dorsiflexion angle and time trial performance differed with respect to strike pattern. These revealed that although dorsiflexion angle was significantly different between rearfoot and mid-to-forefoot strikers [$F(1, 13) = 121.31, p < .001, \eta^2 = .91$]; there was no difference in time trial performance between groups [$F(1, 13) = 2.57, p = .135, \eta^2 = .176$]. With respect to contact time, curve estimation suggested almost comparable fit for a quadratic compared to a linear regression equation to characterise the relationship between contact time and time trial time [Quadratic: $r^2(13) = .574$, Adjusted $r^2(13) = .496, F(2,13) = 7.409, p = .009$; Linear: $r^2(13) = .567$, Adjusted $r^2(13) = .530, F(2,13) = 15.68, p = .002$].

Inspection of the graphical representations of the relationships between the measures of the children’s running kinematics suggested that dorsiflexion angle at foot strike and maximal knee flexion angle were related to maximal hip adduction angle and that loading rate was related to peak ground reaction force. The graphs concerned are shown in Fig. 3 (Supplementary material). Pearson’s correlations revealed that a higher loading rate was very strongly correlated with higher peak ground reaction force [$r(13) = .925, p < .001$]. Pearson’s correlations also showed that a lower maximal hip adduction angle during stance was strongly correlated to

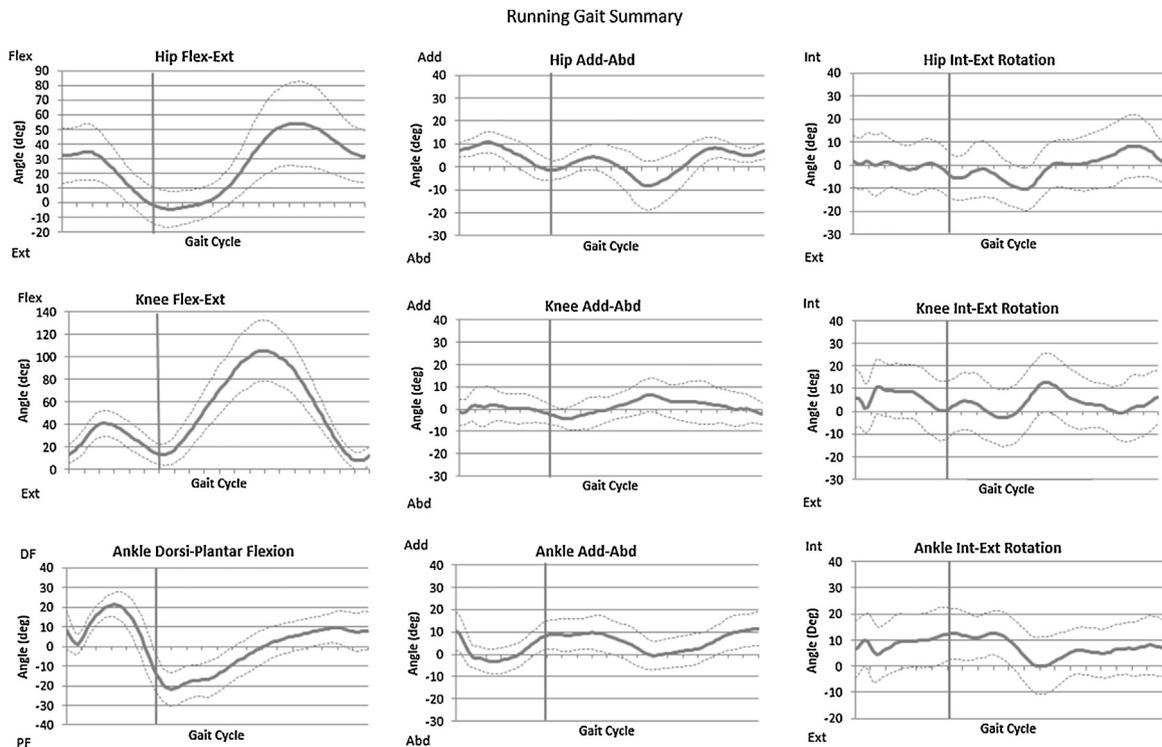


Fig. 1. Kinematic graphs representing the average and standard deviation of sagittal, frontal and transverse plane (organised by columns) for the hip, knee and ankle joints (organised by rows) during one complete gait cycle of running (foot strike to foot strike). The vertical line represents the average time point for foot-off, marking the end of the stance phase.

a higher maximal knee flexion angle [$r(13) = .557, p = .04$] and a higher dorsiflexion angle at footstrike [$r(13) = .63, p = .02$].

4. Discussion

The purpose of this study was to investigate the biomechanics of running in typically developing, physically active, prepubescent children and to examine how children's running kinematics related to their running performance. Results show children who run faster during the time trial typically have a longer stride length but a shorter contact time and tend to land with a mid-to-forefoot striking pattern (smaller ankle dorsiflexion angle). The data also revealed that the kinematics of the hip in the frontal plane are strongly related to those of the knee and the ankle in the sagittal plane.

In this study, longer stride length was strongly associated with better running performance in children; although curve estimation suggested that there was an upper limit for stride length passed which running performance decreased. This finding is consistent with studies in adults which have reported that skilled endurance runners tend towards using a longer stride length for a given velocity than less skilled runners,¹¹ but that elite distance runners have a shorter overall stride length than amateurs.^{11,12} In adults, the ability to optimise stride length is clearly expertise dependent and therefore modifiable through training.

Likewise, contact time in adults is thought to fall within an optimal range,¹³ favoring a shorter contact time for more economical running gait^{24,25} which can be achieved through training, specifically in plyometric exercises.²⁶ In our study, there was a strong correlation between the contact time and running performance with the faster children exhibiting shorter contact times. Nonetheless, curve estimation suggested that it is possible that there may have been a lower limit beyond which decreasing contact time was detrimental to running performance. Given that plyometric conditioning exercises are practicable for prepubescent children and have been used in a number of prepubescent athletic populations,^{27,28} a well-structured program may be a viable method of improving endurance running performance in children.

Perhaps unsurprisingly, research has shown that a concurrent relationship exists between contact time, striking pattern and running economy. Di Michele and Merni²⁹ reported for a given contact time, a midfoot striking pattern is more economical and that increasing contact time improves economy regardless of striking pattern. While our data did show a strong correlation between less dorsiflexion at footstrike and a faster time trial, there was no significant difference in time trial performance between children who ran with a mid-to-forefoot striking pattern compared to a rearfoot striking pattern. Consequently, our data suggested that in children, much like in adults, that the concurrent relationship between contact strike and striking pattern affects running performance more so than either contact time or striking pattern in isolation.

Although our study did not reveal a relationship between the hip and knee kinematics of the children and their running performance, there was nonetheless a clear relationship between the kinematics of the hip, knee and ankle. A wider stance (lower maximal adduction angle) was correlated with a greater maximal knee flexion angle and a more dorsiflexed ankle at footstrike. A wider stance, potentially due to weakness of the hip abductors, can lead to inadequate shock absorption at the hip which may contribute to chronic injury processes in the long term such as sacral stress fractures or osteitis pubis.^{13,24} One way of compensating for poor shock absorption at the hip is to transfer shock absorption to more distal joints in the kinematic chain. This type of running gait, characterized by increased knee flexion and consequently termed "Groucho running", has been shown to reduce shock transmission through

the body but at the expense of running economy.²⁴ In our study, deeper knee flexion was accompanied by greater ankle dorsiflexion at footstrike which is consistent with previous studies in adults.³⁰ Again, this may represent a compensatory measure, but in this instance aimed at mitigating the consequences of a "Groucho running" gait on running economy by prolonging contact time. This would appear to be a successful strategy with respect to children's running performance given that our results showed that neither lower maximal hip adduction angle nor greater maximal flexion knee angle were correlated with a slower time trial.

5. Conclusion

The findings of our study suggest that many of the key biomechanical indicators of running economy in adults also correlate with running performance in prepubescent children. Our data suggest that stride length in particular is a strong indicator of running performance in prepubescent children much as it has been shown to correlate with running economy in adults.¹¹ Although both contact time and dorsiflexion angle at footstrike were shown to correlate with running performance in children, it would appear best to consider them with respect to each given that no significant difference was found between rearfoot and mid-to-forefoot strikers. Much like in adults,¹⁴ optimising running gait to improve performance in children would appear to require balancing global measures of gait such as stride length, contact time and striking pattern. Likewise, when considering the effect of gait on the potential to develop a chronic injury process, it would appear that the kinematic chain must be considered as a whole rather than focus being directed to one joint segment in isolation from those proximal and distal. In future, attention should be directed to determining whether plyometric training is a viable method of facilitating such changes in the running gait, running performance and running related injury prevalence of prepubescent children.

Practical implications

- Much like adult running, specific biomechanical characteristics of children's running are strongly linked to performance
- Increased stride length and reduced contact time are strong indicators of running performance in prepubescent children.
- Children demonstrated variability in foot strike patterns, with no significant difference in running performance.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <https://doi.org/10.1016/j.jsams.2018.05.025>.

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