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Investigation of biomechanical strategies increasing walking speed in young children aged 1 to 7 years*

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Abstract. For young children, biomechanical joint maturation is achieved at 4 years old for the ankle, at about 6–7 years for the knee, at 6 for the hip. These differences may involve different propulsion strategies with respect to age and particularly to increase walking speed. One hundred and six children are included in the study. Mechanical work during the stance phase was computed and an involvement ratio for each joint was deduced (work of one joint divided by the sum of the works of the three joints). Whatever the age, the biomechanical strategy to increase speed is similar for the positive work: increase of the ankle involvement and decrease of the hip involvement. The negative work is mainly produced by the knee whatever age.

Key words: Gait, children, walking speed, age, mechanical work

Résumé. Étude des stratégies biomécaniques pour augmenter la vitesse de marche chez le jeune enfant de 1 à 7 ans.

Chez le jeune enfant, la maturation articulaire est atteinte à des âges différents pour la cheville (4 ans), le genou (6–7 ans) et la hanche (6 ans). Ces différences peuvent entraîner différentes stratégies de propulsion, en particulier, pour augmenter la vitesse de marche. Cent six enfants sont inclus dans l'étude. Le travail mécanique au cours de la phase d'appui est calculé et le ratio d'implication de chaque articulation est déduit (travail d'une articulation divisé par la somme des travaux des trois articulations). Quel que soit l'âge, la stratégie d'augmentation de vitesse est similaire pour le travail positif : augmentation de l'implication de la cheville, diminution de celle de la hanche. Le travail négatif est principalement fourni par le genou, pour tous les âges.

Mots clés : Marche, enfant, vitesse, âge, travail mécanique

1 Introduction

For young children, biomechanical gait parameters are influenced by age and walking speed (Samson, *et al.*, 2013, Schwartz, Rozumalski, & Trost, 2008). The influence of speed variation on biomechanical gait parameters was largely studied for children. On the one hand, Stansfield, *et al.*, (2001a, 2001b) concluded that speed variation was more influential than age variation for comparisons of young children gait, and that dimensionless speed should be preferentially considered rather than age to compare

healthy and pathological gait in children. Children included in this study were between 7 to 12 years old. On the other hand, Schwartz, *et al.* (2008) described the gait of 83 typically developing children walking at a wide range of speed displaying spatio-temporal, kinematic, dynamic and electromyographic data, for children between 4 and 17 years old. In this study, the influence of speed variation was obvious from the graphs presented, but age influence was not studied. Furthermore, young children present a high intra-individual gait speed variability, especially under 4 years old (Müller, Müller, Baur & Mayer, 2013) providing a large range of speeds in gait analyses. Therefore, it is essential to consider speed effect, and understand speed variation strategies in this population.

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Actually, pathologic populations often walk slower and this has to be taken into account to compare healthy and pathological gaits (Van Hamme *et al.*, 2015). Additionally, Samson, *et al.* (2013) demonstrated that biomechanical joint maturation was different from ankle to knee and hip. In this study, the authors conclude that “the biomechanical maturation of joint dynamics occurred around an age of 4 years for the ankle and between 6 and 7 years for the knee and the hip”. From a methodological point of view, for this study, the wide speed range available was reduced (selecting a specific range around the mean speed) in order to allow age groups comparison with equivalent walking speed. Another study also demonstrated the important contribution of hip for gait propulsion for children compared to the adults (Samson, Desroches, Chèze, & Dumas, 2009). Calculating a global net joint for the whole body, Van de Walle, *et al.* (2010) concluded that positive work was similar from 3 to 35 years old, whereas negative work was mature at 9 years old (diminution in absolute value). These results suggest that biomechanical maturation resides in different contribution of each joint regarding the others and not in variation of the global mechanical work. Nevertheless, the contribution of each joint to a speed increase remains unclear in young children.

In addition, a recent study demonstrated that children with developmental coordination disorders and healthy children adopt different propulsion strategies (Diamond, Downs, & Morris, 2014). In this study, the authors used curve peaks of ankle and hip power to compare propulsion strategies.

Regarding healthy adults, increasing speed is achieved by an increase of positive work at hip and ankle and an increase of negative work at knee joint (Jonkers, Delp & Patten, 2009; Silverman, *et al.*, 2008). Modification of these strategies appears for older people with more involvement of hip work than ankle work to increase speed, because of the disability of the ankle (Cofré, Lythgo, Morgan & Galea, 2011).

Using an original method, considering work ratio between ankle, knee and hip, (Chen, Kuo & Andriacchi, 1997) characterized the influence of walking speed on mechanical joint power of children aged from 5 to 11 years. For this population, works at the knee and the hip were influenced by speed variation whereas work at the ankle did not. Unfortunately, the effect of age variation was not considered in this study.

Then, the contribution of each joint to a speed increase remains unclear in young children and regarding existing differences in joint maturation and the influence of both age and walking speed on the biomechanical gait parameters, it can be hypothesized that, depending on age, children might present different strategies to increase speed. Therefore, the objective of the present study is to investigate, with respect to the ankle, knee and hip joints, the biomechanical strategies used by children aged from one to seven years to increase walking speed.

2 Materials and methods

2.1 Population and experimental set-up

Gait analysis was performed on 106 healthy children (from one to seven years old). Participant characteristics are presented in Table 1. All of the children were independent walkers from the first examination (no minimal walking experience was required) and clinical examination did not reveal any orthopaedic or neurological disorders. The local ethic committee approved the study. The children were included in the study after clinical examination when their parents consent to involvement after having been informed about the protocol.

Twenty-four skin markers were fixed on anatomical landmarks of the pelvis (the right and left anterior and posterior superior iliac spines) and the lower limbs (the great trochanter, medial and lateral epicondyles, anterior tibial tuberosity, medial and lateral malleoli, calcaneus, first and fifth metatarsal heads and hallux) (Samson, *et al.*, 2009, 2013).

The children walked barefoot at a self-selected speed. Fifteen to twenty gait trials were measured for each subject using a Motion Analysis[®] system with eight Eagle[®] cameras (Motion Analysis Corporation, Santa Rosa, California, USA) at 100 Hz and three Bertec[®] force platforms (Bertec Corporation, Columbus, Ohio, USA) at 1000 Hz. Only trials with valid dynamic data (*i.e.*, one foot and only one on one forceplate) were selected, providing between one to six trials per gait analysis. Finally, 1253 gait cycles were retained.

2.2 Data processing

After filtering (low-pass zero-lag, 4th-order, Butterworth filter, with a 6-Hz cut-off frequency), the marker trajectories were obtained in an Inertial Coordinate System (ICS) (Wu & Cavanagh, 1995). The hip joint centre localisation was determined using the regression models established by Harrington, Zavatsky, Lawson, Yuan, and Theologis (2007), selecting only the data of healthy children. The inertial parameters were determined using the regressions established by Jensen (Jensen, 1989). The three orthogonal axes (X, Y, and Z) corresponding to each segment coordinate system (SCS) were built following the International Society of Biomechanics recommendations (Wu, *et al.*, 2002). A quaternion was extracted from the attitude of these segment axes in the ICS. The angular velocities of the proximal and distal segments were obtained in the ICS using quaternion algebra and were subtracted to compute the (relative) joint angular velocity, ω . The net 3D joint moments, $\mathbf{M}$, were computed in the ICS by bottom-up inverse dynamics (Dumas, Aissaoui, & Guise, 2004) with the force platforms data re-sampled at 100 Hz. The joint power, P , was computed in 3D by the dot product between $\mathbf{M}$ and ω . The joint moments, $\mathbf{M}$, were then expressed in the joint coordinate systems (Desroches,

Table 1. Children characteristics depending on age and speed groups.

Age group (years)	Age (years)	Leg length l_0 (m)	Mass m_0 (kg)	Number of children (including number of boys)	Number of trials	Speed groups	Number of trials	Speed (dimensionless)			
	Mean (SD)	Mean (SD)	Mean (SD)					Mean	SD	Min	Max
[1–2]	1.52 (0.26)	0.34 (0.02)	11.04 (0.93)	45 (19)	205	low	68	0.26	0.05	0.09	0.33
						med	69	0.37	0.03	0.33	0.42
						high	68	0.50	0.05	0.43	0.62
[2–3]	2.4 (0.29)	0.4 (0.03)	13 (1.32)	54 (28)	246	low	82	0.29	0.05	0.14	0.35
						med	82	0.40	0.03	0.35	0.44
						high	82	0.51	0.05	0.44	0.66
[3–4]	3.38 (0.27)	0.45 (0.03)	15.33 (1.92)	52 (25)	267	low	89	0.29	0.06	0.11	0.36
						med	89	0.40	0.03	0.36	0.44
						high	89	0.52	0.06	0.44	0.71
[4–5]	4.44 (0.28)	0.5 (0.03)	17.52 (2.23)	38 (17)	198	low	66	0.34	0.06	0.17	0.41
						med	66	0.44	0.02	0.41	0.47
						high	66	0.53	0.04	0.47	0.62
[5–6]	5.42 (0.28)	0.55 (0.04)	20.05 (2.57)	40 (18)	204	low	68	0.34	0.06	0.15	0.4
						med	68	0.44	0.02	0.4	0.48
						high	68	0.53	0.04	0.48	0.69
[6–7]	6.55 (0.34)	0.59 (0.03)	22.31 (3.02)	24 (9)	133	low	44	0.39	0.04	0.28	0.44
						med	45	0.47	0.02	0.44	0.51
						high	44	0.55	0.02	0.51	0.6

Chèze, & Dumas, 2010), and $\mathbf{M}$ and P were re-sampled on a percentage of the gait cycle and expressed using the dimensionless scaling strategy (Hof, 1996), with body mass and leg length (the distance from the ground to the great trochanter) used as metric values. The walking speed was defined from the initial contact of one foot to the next initial contact of the same foot (one gait cycle) and expressed with a dimensionless parameter (Hof, 1996). The moments are in $\text{N.m}/m_0gl_0$, the powers are in $\text{W}/m_0\sqrt{g^3.l_0}$, the GRF is in N/m_0g and the walking speed is in $\text{m.s}^{-1}/\sqrt{g.l_0}$ (with m_0 indicating the body mass, l_0 , the leg length and g , the acceleration of gravity).

2.3 Data analysis

Children were grouped according to their age (1 group per year). For each age group, gait trials are divided into 3 speed groups: slow, medium, high speed depending on distribution (*i.e.*, low: 1–33rd percentile, medium: 34–66th percentile, high: 67–100th percentile). To study propulsion, mechanical work (W , area under the entire power curve in $\text{Joules}/m_0\sqrt{g^3.l_0}$) was processed for ankle, knee and hip joints during the stance phase. Then, for each joint, two involvement ratios were deduced, one for positive work and one for negative work (*e.g.*, for ankle, the positive ratio was $W_{\text{ankle}}^+/(W_{\text{ankle}}^+ + W_{\text{knee}}^+ + W_{\text{hip}}^+)$ the same method is adopted with negative data, and designated W_{joint}^-). Statistical analysis was performed on these involvement ratios to test significant differences due to speed variation within age group (Wilcoxon and Kruskal-Wallis tests, $p < 0.05$).

3 Results

Children characteristics and gait trials distribution are detailed in Table 1.

For each age group, about 200 gait cycles or more were obtained, except for the 6–7 years old group with 133 gait trials. We can also notice that mean walking speed increases slightly with age, even if dimensionless speed was considered ($0.37 \text{ m.s}^{-1}/\sqrt{g.l_0}$ for 1–2 years-old, $0.47 \text{ m.s}^{-1}/\sqrt{g.l_0}$ for 6–7 years). Moreover, the range speed for very young children was larger than that for the older ($0.53 \text{ m.s}^{-1}/\sqrt{g.l_0}$ vs $0.32 \text{ m.s}^{-1}/\sqrt{g.l_0}$).

According to the mechanical works, the evolution with speed was globally similar whatever the age (Tab. 2). Increasing of walking speed involved increasing of W_{ankle} , decreasing of W_{knee} (negative work, *i.e.*, increase in absolute value) and increasing of W_{hip} . For children under 4 years, W_{ankle} was mainly negative for the low speed and became positive when speed increased. W_{knee} was always negative, included for the youngest children and slowest speeds whereas W_{hip} was always positive.

Concerning the involvement ratios, the global evolution with walking speed was similar whatever the age (Fig. 1). Knee ratios for positive work, and hip ratios for negative work were not presented because median, 1st quartile and 3rd quartile were equal to zero for almost all groups (except for the group 1–2 years old, for the knee ratio involvement in positive work, 3rd quartile were 10% and 2% for the low and the high speed respectively).

Regarding positive work, more than 70 % of this work was provided by hip, for all age-speed subgroups. This ratio significantly decreased when the child walked faster

Table 2. Mechanical work for ankle, knee and hip by age and speed groups. Median values, 1st quartile (Q1) and 3rd quartile (Q3).

Age Group (years)	Speed groups	W_{ankle}	W_{knee}	W_{hip}
		Median [Q1;Q3] (dimensionless)	Median [Q1;Q3] (dimensionless)	Median [Q1;Q3] (dimensionless)
[1–2]	low	−0.18 [−0.34;−0.07]	−0.10 [−0.37;0.16]	1.20 [0.66;1.70]
	med	0.01 [−0.17;0.23]	−0.26 [−0.60;−0.01]	2.08 [1.61;2.64]
	high	0.37 [0.08;0.74]	−0.45 [−0.75;0.09]	2.67 [2.04;3.29]
[2–3]	low	−0.05 [−0.21;0.13]	−0.16 [−0.33;−0.01]	1.38 [0.96;1.78]
	med	0.22 [−0.07;0.47]	−0.28 [−0.51;−0.13]	1.79 [1.42;2.27]
	high	0.50 [0.11;0.89]	−0.58 [−0.85;−0.32]	2.34 [1.82;2.81]
[3–4]	low	−0.01 [−0.26;0.21]	−0.22 [−0.42;0.01]	1.35 [1.00;1.63]
	med	0.21 [0.02;0.4]	−0.42 [−0.54;−0.22]	1.65 [1.32;2.18]
	high	0.64 [0.29;1.06]	−0.65 [−0.85;−0.45]	2.35 [2.00;2.80]
[4–5]	low	0.11 [−0.11;0.39]	−0.25 [−0.39;−0.08]	1.38 [1.07;1.62]
	med	0.56 [0.33;0.86]	−0.44 [−0.65;−0.28]	1.81 [1.40;1.99]
	high	0.93 [0.51;1.15]	−0.69 [−0.83;−0.43]	2.10 [1.85;2.61]
[5–6]	low	0.14 [−0.17;0.32]	−0.29 [−0.48;−0.14]	1.25 [0.96;1.46]
	med	0.38 [0.18;0.58]	−0.45 [−0.62;−0.27]	1.55 [1.34;1.89]
	high	0.63 [0.43;0.76]	−0.50 [−0.78;−0.33]	1.92 [1.41;2.30]
[6–7]	low	0.20 [0.04;0.35]	−0.30 [−0.44;−0.18]	1.27 [1.01;1.54]
	med	0.51 [0.33;0.68]	−0.47 [−0.64;−0.29]	1.60 [1.38;2.03]
	high	0.75 [0.61;0.95]	−0.72 [−0.89;−0.55]	1.96 [1.75;2.46]

Fig. 1. Ratios involvement for the 6 age groups and the 3 speed groups: a. ankle ratio in positive work, b. hip ratio in positive work, c. ankle ratio in negative work, d. knee ratio in negative work. The height of the color bars represent the medians, the dark lines represent the 1st and 3rd quartile. The stars represent significant differences between speed groups (Kruskal-Wallis and Wilcoxon tests, $p < 0.05$).

leading more involvement of ankle. Knee joint was poorly involved in positive work (3rd quartile at 10 % for low speed of 1–2 years old group), and its involvement decreased with the increase of speed.

A notable point about the evolution of positive ratios with speed concerned the ankle joint. The difference of involvement between slow and fast walking speed was more important for younger children (multiplied by 5 for the children under 2 years old and multiplied by 2 for children older than 4). Ankle involvement ratio was significantly different between speed groups for all age groups.

Concerning the negative work, the knee was predominantly involved (with more than 60%, except for the low speed for the youngest children), and this part was higher when speed increased, with diminution of ankle ratio. Ankle involvement ratio decreased significantly while speed increased between low and medium speed for all age groups, and between medium and high speed only for children younger than 4 years old. Hip involvement was almost non-existent in negative work.

4 Discussion & Conclusion

Influence of speed variation on spatio-temporal, kinematic and dynamic gait parameters was largely studied and demonstrated for children (Dusing & Thorpe, 2007; Schwartz, *et al.*, 2008; Stansfield, Hillman, Hazlewood, & Robb, 2006; Stansfield, *et al.*, 2001a, 2001b) even if the studies of very young children were few.

The present study proposed an original method, considering mechanical work during the stance phase, to quantify the biomechanical joint strategies to increase speed at each age for children from one to seven years old. Conversely, many studies in the literature were based on comparison of curves peaks (Diamond, *et al.*, 2014; Schwartz, *et al.*, 2008; Stansfield, *et al.*, 2006, 2001a, 2001b; Van der Linden, Kerr, Hazlewood, Hillman, & Robb, 2002), considering only extreme values of kinematic and dynamic parameters and not the whole curve area (during stance phase). In our study, biomechanical joint strategy evolution with speed was similar whatever the age, despite the existing discrepancies on biomechanical maturation of the joints described in previous studies (Samson, *et al.*, 2009, 2013). Nevertheless, the present study pointed out that because very young children principally use their hip joint for gait propulsion (Samson, *et al.*, 2009), they have to recruit their ankle muscles to increase speed and, thus, to produce more positive work. It is worth noting that this result should be considered for shoe design as interaction between shoe and ankle joint has been demonstrated (Samson, Dohin, Van Hamme, Dumas, & Chèze, 2011; Wegener, Hunt, Vanwanseele, Burns, & Smith, *et al.*, 2011; Wolf, Simon, Patikas, Schuster, & Armbrust, *et al.*, 2008).

Knee was poorly involved in propulsion (positive work), while its role was very important in braking phase

(negative work). This phenomenon may explain the non-consideration of knee joint in the study of Diamond, *et al.* (2014) which quantify the propulsion strategy during gait and running, comparing children with developmental coordination disorders and typically developing children. The analysis of the joint involvement ratios was proposed in the present study. Van der Linden, Kerr, Hazlewood, Hillman, & Robb (2002) led a similar study with children around 9 years old at clinically relevant speeds (lower than the normal speeds) and pointed out the large variation of kinematics and joint moments, but power was not considered in this study.

The present study considered dimensionless parameters, in accordance with literature recommendations (Hof, 1996; Sutherland, 1997), allowing comparison of children on a large range of age (*i.e.*, with differences in heights and leg lengths). Moreover, speed groups were based on the natural distribution for each age group, taking into account the eventual differences in median speed. Other authors preferred choosing a fixed range of speed, with constant step (*e.g.*, 0.1 dimensionless speed) for all age groups (Schwartz, *et al.*, 2008, Van der Linden, *et al.*, 2002). Conversely, all of the gait trials were recorded at self-selected speed by children, giving few speed variations for children older than 4 years. Acquiring trials with specific instructions about low or high speeds would complete the information about propulsion strategies for extreme speeds, such as Schwartz, *et al.* (2008) proceeded. Nevertheless, very young children may not be able to follow this kind of instructions.

The main limit of this study was the consideration of lower limbs only. Getting information about whole body would have involved the use of more skin markers on child body (*i.e.*, on head, trunk and arms) that is not easily applicable for experimental protocol included very young children. In response to this problem, some authors (Hallemans, Aerts, Otten, De Deyn, & De Clercq, 2004) chose to use a tight fitting suit to glue the markers on it, involving markers displacements with respect to skin and then increasing measurement errors.

With respect to mechanical work, calculated in the present study for the ankle, knee and hip joints, other methods have been proposed in the literature to study gait. For example, external work can be computed using the velocity of the center of mass (Cavagna, 1985) or using the velocity of the center of mass and the ground reaction force (Donelan, Kram, & Kuo, 2002). Segmental approaches were also proposed (Robertson & Winter, 1980). These are several views of the same concept, either at a global or a local level. It is the joint work that has been analyzed in the present study in order to complete the joint moments and power that were previously analyzed on the same population (Samson, *et al.*, 2013).

The ratio of 70% of positive work for hip joint could appear high comparing adult population where ankle is the joint most involved in positive work (Robertson & Winter, 1980). This can be explained by the pattern of the hip power for young children which is positive

during stance phase, contrarily to that of adults as shown in a previous study (Samson, *et al.*, 2009). Moreover, it is worth noting that, in the present study, power was calculated in 3D (*i.e.* not considering only the flexion/extension moment) and for the hip, abduction and internal rotation moments were not negligible. This may explain the positive hip power during the whole stance phase. Absence of adult data obtained with same methodology (3D power) is a limit of the present study. Nevertheless, influence of speed on mechanical work on adults was already explored, especially for old people (Chen, *et al.*, 1997; Cofré, *et al.*, 2011; Jonkers, *et al.*, 2009; Silverman, *et al.*, 2008). In the literature, the joint moments and power, as well as the spatio-temporal parameters, and joint angles appear to be obviously modified by speed variation. The present study additionally concludes that the general biomechanical strategy to increase speed was similar for children from one to seven years old, considering the lower limb joints involvement in both positive and negative work. More than 70 % of the positive work was provided by hip, but the involvement of ankle joint increased to walk faster, especially for the youngest children, while the negative work was mainly related to knee joint, with a decrease in ankle involvement when speed increased, again, especially for the youngest children.

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