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Foot mechanics during the first six years of independent walking

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ABSTRACT

Recognition of the changes during gait that occur normally as a part of growth is essential to prevent mislabeling those changes from adult gait as evidence of gait pathology. Currently, in the literature, the definition of a mature age for ankle joint dynamics is controversial (i.e., between 5 and 10 years). Moreover, the mature age of the metatarsophalangeal (MP) joint, which is essential for the functioning of the foot, has not been defined in the literature. Thus, the objective of the present study explored foot mechanics (ankle and MP joints) in young children to define a mature age of foot function.

Forty-two healthy children between 1 and 6 years of age and eight adults were measured during gait. The ground reaction force (GRF), the MP and ankle joint angles, moments, powers, and 3D angles between the joint moment and the joint angular velocity vectors (3D angle $\alpha_{M.\omega}$) were processed and compared between four age groups (2, 3.5, 5 and adults).

Based on statistical analysis, the MP joint biomechanical parameters were similar between children (older than 2 years) and adults, hinting at a quick maturation of this joint mechanics. The ankle joint parameters and the GRFs (except for the frontal plane) showed an adult-like pattern in 5-year-old children. Some ankle joint parameters, such as the joint power and the 3D angle $\alpha_{M.\omega}$ still evolved significantly until 3.5 years. Based on these results, it would appear that foot maturation during gait is fully achieved at 5 years.

1. Introduction

Recognition of the changes that occur normally as a part of growth and body development is essential to prevent mislabeling those changes from adult gait as evidence of gait pathology (Sutherland, 1997). At the foot level, children may reveal numerous variations (e.g., clubfoot, planovalgus, pes planus, equinus and flat foot). There is therefore a need to better define and quantify the foot function during growth.

Several approaches have been reported in the literature to better understand the foot mechanics during gait in young healthy children (i.e., younger than 6 years). They include the assessment of plantar pressure distribution (Alvarez et al., 2008; Bosch et al., 2007; Hallemans et al., 2006b, 2003; Bertsch et al., 2004; Hennig et al., 1994; Hennig and Rosenbaum, 1991), ground reaction force (GRF) (Hallemans et al., 2006a; Diop et al., 2005; Stansfield et al., 2001b; Sutherland, 1997; Preis et al., 1997; Takegami, 1992; Beck et al., 1981), and ankle joint kinematics and dynamics (Chester and Wrigley, 2008; Chester et al., 2006; Hallemans et al., 2006b, 2005; Ganley and Powers, 2005; Cupp et al., 1999; Sutherland, 1997; Oeffinger et al., 1997; Stansfield et al., 2001a; Ounpuu et al., 1991).

Studies on plantar pressure distribution in young children have shown predominant use of the midfoot to the detriment of the heel and forefoot. This predominance has been explained by the immaturity of the foot skeletal structures and the importance of the fat pad (Alvarez et al., 2008; Bosch et al., 2007; Hallemans et al., 2006b, 2003; Bertsch et al., 2004; Hennig et al., 1994). According to these studies, mature plantar pressure distribution is obtained between 5 and 6 years of age.

With regard to GRF results, Hallemans et al. (2006a) reported modifications of the curve pattern of the vertical component from one hump to two humps during the first steps of independent walking which the authors attributed to roll-off immaturity. However, depending on the study, conclusions regarding the definition of a mature age for GRFs patterns varied extensively: from 3 to 8 years

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(Diop et al., 2005; Stansfield et al., 2001b; Sutherland, 1997; Preis et al., 1997; Takegami, 1992; Beck et al., 1981).

In contrast to plantar pressure approaches, few studies have explored ankle biomechanical parameters before 6 years of age (Hallemans et al., 2006b, 2005; Chester et al., 2006; Sutherland, 1997). With respect to joint angles, moments and powers, conclusions regarding maturity of ankle joint were controversial: the ankle joint mechanics was defined as mature between 5 years (Ounpuu et al., 1991), 8 years (Cupp et al., 1999), 9–13 years (Chester and Wrigley, 2008; Chester et al., 2006), or 10 years (Oeffinger et al., 1997).

Like the ankle, the toes are essential for the functioning of the foot (Bojsen-Møller and Lamoreux, 1979). "Toe dorsiflexion secures support to the longitudinal arch at peak loads, and it enables the ball (i.e., part of the foot composed of the distal heads of the metatarsals and their surrounding fat pad) to withstand the tangential forces to which it is exposed. Toe dorsiflexion also allows the foot to take advantage of different leverage ratios to suit different conditions, resulting in more efficient propulsion". Similar to the joint kinematic and dynamic changes during growth, it could be hypothesized that the metatarsophalangeal (MP) joint is not mature immediately after performing the first

Table 1
Anthropometric and temporal distance parameters for the four groups. Significant differences are shown with a *p*-value less than 0.05 (a,b,c: significant difference between group 1 and groups 2 to 4, respectively; d,e: significant difference between group 2 and groups 3 and 4, respectively; f: significant difference between groups 3 and 4; n.s: no significant difference between groups; l_0: leg length; *g*: acceleration of gravity).

	Group 1	Group 2	Group 3	Group 4	
N	14	14	14	8	
Age range (years)	1.2–2.8	2.9–4.2	4.3–5.8	23.0–31.0	
Mean Age (years)	2.1 ± 0.5	3.6 ± 0.4	5.0 ± 0.5	25.0 ± 2.6	abcdef
Height (cm)	86.9 ± 5.2	100.8 ± 5.8	110.8 ± 6.8	175.0 ± 4.0	abcdef
Mass (kg)	12.2 ± 1.6	16.5 ± 2.3	18.6 ± 3.2	67.0 ± 5.6	abcdef
Step length (m/l_0)	1.10 ± 0.13	1.34 ± 0.13	1.38 ± 0.13	1.67 ± 0.05	abcef
Walking speed ($m.s^{-1}/\sqrt{(gl_0)}$)	0.28 ± 0.03	0.33 ± 0.39	0.39 ± 0.03	0.47 ± 0.02	bcdef
Cadence ($Hz/\sqrt{(g/l_0)}$)	0.82 ± 0.07	0.88 ± 0.08	0.74 ± 0.06	0.73 ± 0.02	n.s
Stance duration (% of gait cycle)	65.4 ± 2.6	64.8 ± 2.68	63.8 ± 1.9	63.7 ± 1.1	n.s

Table 2
GRF, MP and ankle variables for statistical analysis. Significant differences are shown with a *p*-value less than 0.05 (a,b,c: significant difference between group 1 and groups 2 to 4, respectively; d,e: significant difference between group 2 and groups 3 and 4, respectively; f: significant difference between groups 3 and 4; n.s: no significant difference between groups; RoM: range of motion; K.W: Kruskal–Wallis test).

Variables		K.W.	1–2	1–3	1–4	2–3	2–4	3–4
GRF								
Ry1	Max. vertical force at early stance	0.248						
Ry2	Max. vertical force at pre-swing	**0.038**	**0.039**	**0.043**	**0.003**	0.679	**0.031**	0.062
Rx1	Max. posterior force at early stance	0.607						
Rx2	Max. anterior force at pre-swing	**0.000**	0.141	**0.001**	**0.002**	0.060	**0.007**	0.062
Rz1	Max. lateral force at early stance	**0.012**	0.232	0.129	**0.002**	0.854	**0.005**	**0.004**
Rz2	Max. lateral force at pre-swing	0.153						
MP								
MP-RoMz	RoM in flex./ext.	0.352						
MP-A_{z1}	Max. ext. at midstance	0.249						
MP-A_{z2}	Max. flex. at pre-swing	0.056						
MP-M_z	Max. ext. moment at midstance	0.875						
MP-M_x	Max. ev. moment at midstance	0.115						
MP-M_x	Max. abd. moment at pre-swing	0.257						
MP-P_1	Max. abs. energy at midstance	0.395						
MP-P_2	Max. gen. energy at pre-swing	0.248						
MP-3DA	Min. 3D angle $\alpha_{M.\omega}$ at pre-swing	0.153						
Ankle								
A-RoM_z	RoM in dorsiflex./plantarflex.	0.181						
A-RoM_x	RoM in inv./ev.	0.422						
A-RoMy	RoM in abd./add.	0.934						
A-Az1	Max. dorsiflex. at midstance	0.248						
A-Az2	Max. plantarflex. at pre-swing	0.093						
A-Az3	Max. dorsiflex. at midswing	0.173						
A-Ax1	Max. ev. at early stance	0.248						
A-Ax2	Max. inv. at pre-swing	0.153						
A-Ax3	Max. ev. at midswing	0.153						
A-Mz	Max. plantarflex. moment at stance	0.697						
A-Mx	Max. ev. moment at midstance	0.391						
A-My	Max. abd. moment at pre-swing	0.114						
A-P1	Max. abs. energy at early stance	**0.008**	**0.014**	**0.011**	**0.001**	0.306	0.067	0.443
A-P2	Max. abs. energy at midstance	0.173						
A-P3	Max. gen. energy at pres-wing	0.875						
A-3DA1	Max. 3D angle $\alpha_{M.\omega}$ at early stance	**0.009**	0.335	0.520	**0.014**	0.335	**0.006**	0.073
A-3DA2	Max. 3D angle $\alpha_{M.\omega}$ at midstance	0.441						
A-3DA3	Min. 3D angle $\alpha_{M.\omega}$ at pre-swing	**0.047**	0.550	0.168	**0.009**	0.781	**0.031**	0.073