Age-related changes in arm motion during typical gait

Peer-reviewed author version

Vandewalle, Patricia; MEYNS, Pieter; Desloovere, Kaat; De Rijck, Jente; Kenis, Julie; VERBECQUE, Evi; Van Criekinge, Tamaya & Hallemans, Ann (2018) Age-related changes in arm motion during typical gait. In: Gait & posture, 66, pag. 51-57.

DOI: 10.1016/j.gaitpost.2018.07.176
Handle: http://hdl.handle.net/1942/26634

Accepted Manuscript

Title: Age-related changes in arm motion during typical gait

Authors: Patricia Van de Walle, Pieter Meyns, Kaat Desloovere, Jente De Rijck, Julie Kenis, Evi Verbecque, Tamaya Van Criekinge, Ann Hallemans

PII: S0966-6362(18)31300-6
DOI: https://doi.org/10.1016/j.gaitpost.2018.07.176
Reference: GAIPOS 6450

To appear in: *Gait & Posture*

Received date: 19-10-2017
Revised date: 23-7-2018
Accepted date: 24-7-2018

Please cite this article as: Van de Walle P, Meyns P, Desloovere K, De Rijck J, Kenis J, Verbecque E, Van Criekinge T, Hallemans A, Age-related changes in arm motion during typical gait, *Gait and Posture* (2018), https://doi.org/10.1016/j.gaitpost.2018.07.176

Title: Age-related changes in arm motion during typical gait

*Patricia **Van de Walle**[a,b,c #,] *Pieter **Meyns**[d], Kaat **Desloovere**[b,c], Jente **De Rijck**[c], Julie **Kenis**[c], Evi **Verbecque**[a], Tamaya **Van Criekinge**[a], Ann **Hallemans**[a]

*Patricia **Van de Walle**[a,b,c] patricia.vandewalle@uantwerpen.be

*Pieter **Meyns**[d]; pieter.meyns@uhasselt.be

Kaat **Desloovere**[b,c] kaat.desloovere@uzleuven.be

Jente **De Rijck**[c]**;** jentederijck@hotmail.com

Julie **Kenis**[c]; julie.kenis@hotmail.com

Evi **Verbecque**[a;] evi.verbecque@uantwerpen.be

Tamaya **Van Criekinge**[a], tamaya.vancriekinge@uantwerpen.be

Ann **Hallemans**[a]; ann.hallemans@uantwerpen.be

a Faculty of Medicine and Health Sciences, University of Antwerp

Universiteitsplein 1, B-2610 Wilrijk, Belgium

b Clinical Motion Analysis Laboratory, CERM

University Hospital Pellenberg

Welligerveld 1, B-3212 Pellenberg, Belgium

c Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, Katholieke Universiteit Leuven

Tervuursevest 101, B- 3001 Heverlee, Belgium

d REVAL Rehabilitation Research Center - BIOMED Biomedical Research Institute, Faculty of Medicine and Life Sciences, Hasselt University, Diepenbeek, Belgium

* Joint first-authors; both authors contributed equally to the current work

Source: Gait and Posture

#Corresponding author:

Patricia Van de Walle

Clinical Motion Analysis Laboratory

University Hospital Pellenberg

Weligerveld 1

3212 Pellenberg

Belgium

Tel +32 16 33 80 13

Fax +32 16 33 80 12

Email: patricia.vandewalle@uantwerpen.be

Highlights

- Reciprocal arm swinging is systematically present at three years of age
- Remnants of guard position can be noticed in young children
- Arm movement in children shows positional changes and increased variation
- Age-related changes but especially increased consistency can be seen until adolescence

Abstract

Background

When toddlers learn to walk, they do so with a typical high guard position of the arms. As gait matures, children develop a reciprocal arm swing. So far, there have been no attempts to describe age-related changes of arm movements during walking after this first rapid development.

Research question

The purpose of this study was to investigate age-related changes in arm movement during typical gait.

Methods

All participants (n=102) received gait analysis using a full-body marker set (Plug-in Gait). Participants were divided into five age-groups: young children (G1: n=20; 3.0-5.9y), children (G2: n=24; 6.0-9.9y), pubertal children (G3: n=26; 10.0-13.9y), adolescents (G4: n=16; 14.0-18.9y) and adults (G5: n=16; 19.0-35.2y). Age-related changes in arm movements were investigated by comparing continuous joint angular waveforms (spm1d) between all groups, as well as by comparing the mean joint angle and range of motion of the different joints between age-groups.

Results

The overall shape of movement patterns was comparable across all age groups. Nevertheless, with advancing age, consistency increased. At the shoulder, G1&2 showed a larger mean extension angle compared to older children and adults. The range of shoulder axial rotation was significantly larger in adults compared to all other age groups. In the youngest groups (G1-G2), an increased mean elbow flexion and mean wrist extension angle was found.

Significance

Determining an exact age of maturation of arm swing remains difficult as parameter specific adult-like values were not reached at the same age but should not be set before the age of ten to fourteen years for any parameter.

Keywords

arm movements; development; age-related; child; walking; gait

Manuscript

1. Introduction

Typically developing infants acquire the ability of independent walking around the age of 12–18 months [1]. At the beginning, toddlers walk with the arms in a fixed posture of shoulder abduction and elbow flexion, a position known as 'high guard', only present during the first months of walking (rapid development phase) and soon developing into a reciprocal arm swing [1-3]. To the best of our knowledge, there have been no attempts to describe age-related changes in arm movements during the following, slower development. In most studies investigating characteristics of a mature adult-like typical arm swing during walking, healthy participants served as a control group studying pathological arm movements during gait [4-7]. However, some authors did focus on the fundamentals of how and why people swing their arms. Specifically, arm swing should be seen as an integral part of gait, most likely with the goal of minimizing energy expenditure and optimizing stability [8]. Although there is some laterality (i.e. the left arm swings on average more than the right [9]), typical arm swing is characterized by largely symmetrical movements, as other studies indicated that this laterality is not significant and arm movements in patients are more asymmetrical [4 5 10], that are coordinated diagonally with the leg movements [11]. Furthermore, arm swing arises mostly from passive dynamics, but active muscle control is required to obtain an out-of-phase coordination with the legs [9 12]. To date, literature describing joint angles of shoulder, elbow and wrist in adults and children is scarce. At the shoulder, range of motion (ROM) is largest for flexion-extension (20°-25°) [7 13-15], followed by axial rotation (12°-14°) [14 15] and shoulder ab-adduction (5°-15°) [13-15]. At the elbow, a flexion-extension motion (15-30°) occurs in flexion [7 13 14]. At the wrist smaller motions of about 10° palmar and dorsiflexion and ulnar and radial deviation take place [13 14]. Furthermore, the range of arm motion will increase when walking faster [16].

Regarding maturation, the changes in arm movements within the first weeks of independent walking are well described [3]. At the end of this short period children lower their arms from the high guard position [1 3]. The first swinging attempts can be observed at the shoulder with the elbows in a flexed posture [2 3]. According to Sutherland et al. reciprocal arm swinging first appears at the age of 1.5 years and is systematically present by the age of 3.5 years [1]. Until now, observations on the following slower development of arm swing patterns are mainly derived from control groups in studies regarding pathological gait [14 15 17]. Hence, investigating age-related changes in arm movements during walking has not yet been primary focus of research. Therefore, it remains unclear at which age different descriptors of arm movements reach mature values. It can be expected that arm swing shows a further maturation (changes in shape, ROM and mean position) and fine-tuning (decrease in variability indicating consistent use of adult-like movements) after this first phase of rapid development. Furthermore, establishing an age-related framework is important for clinical practice, in which total body kinematic measurements, including trunk and arm movements, are being increasingly promoted. As arm movements seem to have an important function in minimizing energy expenditure and optimizing stability, these functions are likely to be affected by deviations in arm swing, either as a direct result of pathology or as compensatory strategy [17]. Age-related reference data of arm movements during walking will allow clinicians to assess whether deviations are related to a lack of maturity or whether they are caused by an underlying pathology or need for compensation.

In the current study, arm movements during walking of typically developing children, adolescents and adults (3-35 years) have been investigated to determine age-related changes. We thereby aimed at gaining insights into maturation and fine-tuning towards an adult-like arm swing pattern and to determine the age at which arm movements during typical gait could be considered mature. This study thereby provides an age-related reference framework for clinical use and future research.

2. Materials and Methods

2.1 Participants

Participants were selected from a database of subjects with typical development created from reference groups recruited for different projects from the Laboratory of Clinical Motion Analysis (University Hospital Leuven) and approved by the appropriate ethical committee [18-20]. For the current study, 118 children and adults with total body three-dimensional gait analysis (3DGA) were eligible. After visibility checks of total body markers sixteen participants were excluded for insufficient visibility. The remaining 102 participants were divided into five age groups: young children (G1; 3.0-5.9 years, n=20); children (G2; 6.0-9.9 years, n=24); pubertal children (G3; 10.0-13.9 years, n=26); adolescents (G4; 14.0-18.9 years, n=16) and adults (G5; 19.0-35.2 years, n=16). Group mean and standard deviation (SD) of anthropometrics are presented in Table 1.

[Table 1 near here]

2.2 Data analysis

During 3DGA, total body kinematics were collected while barefoot walking on a 10-m walkway at comfortable walking speed using an eight to fifteen-camera VICON System (Mx camera-workstation, 100-120 Hz, Plug-In Gait model (*YXZ cardan angles comparing relative orientation of two segments)*, VICON, Oxford Metrics, Oxford, UK) [21]. One gait cycle (left + right step) of three successful walking trials per subject were used for further analysis. Trials were excluded when excessive arm or head movements unrelated to walking, were made. Next to joint angular waveforms (angles versus percentage of the gait cycle) of shoulder (flexion-extension, ab-adduction and internal/external rotation), elbow (flexion-extension) and wrist (palmar-/dorsiflexion and ulnar/radial deviation), following kinematic parameters were analyzed: angle at initial contact (A-IC) and toe off (A-TO), maximal joint angle (peak value), mean joint angle (indicating mean position) and ROM over the gait cycle. The ‘time to peak’ parameters represent the percentage from the total gait cycle where the peak value occurs and are an indication of coordination. Walking speed and Froude number (non-dimensional walking speed) were calculated [22].

$$(Froude\ number\ = \frac{\text{walking speed}}{\sqrt{\text{g x leg length}}}) \qquad (1)$$

2.3 Statistical analysis

Regression analysis for age and walking speed was carried out across the entire gait cycle by means of spm1D. Changes to adult-like values (maturation) of the joint angular time profiles and changes in fine tuning (SD of the joint angular time profile over the six steps per subject) were assessed across the entire gait cycle between groups by means of spm1D, one way ANOVA. Post hoc analysis consisted of two-sample t tests conducted on all group pairs by means of spm1D with Bonferroni correction for multiple analysis per joint [23 24] .

Kinematic parameters were analyzed with IBM® SPSS® Statistics (version 22). Data were normally distributed (Kolmogorov-Smirnov). For comparison of mean values the mean of 3 left and 3 right steps per subject was used as left and right side were not found to be different. To investigate maturation a General Linear Model with group as fixed factor and Froude number as a covariate was defined. Both main and possible interaction effects were investigated. Differences between age groups were investigated by pairwise post hoc comparisons (Tukey HSD) with significance level set at $p<0.05$. To investigate fine tuning, SD was calculated over the six steps per subject [14] and compared between age groups.

3. Results

Walking speed and Froude number showed significant ($p<0.001$) differences between age groups, gradually increasing with age (Table 1). Normalized to Froude number, G4 showed the lowest values. Significant main effects of Froude number were found for shoulder ROM in sagittal and transverse plane, elbow ROM, wrist ROM in sagittal and transverse plane and for peak value and A-TO of wrist palmar/dorsiflexion. A significant interaction effect between Froude number and age group was only found for shoulder rotation ROM and wrist dorsi-/palmar flexion.

Kinematic parameters describing arm swing per age group for mean values and consistency are presented in table 2, joint angular waveforms over the gait cycle in Figure 1 and Appendix 1 & 2.

Age-related changes in joint angular wave forms and mean values (maturation)

The *overall patterns* were similar (increase in joint angle from IC to a single peak value around opposite IC) across all groups indicating an early onset (already in G1) of an adult-like arm swing pattern (Figure

2). *Time to peak* ranged from 42.1% to 56.5% of the gait cycle with no significant differences between groups. Regression analysis revealed a significant effect of age at the shoulder in the sagittal plane (total GC) and transverse plane (around TO).

[Figure 1 near here]

[Figure 2 near here]

At the shoulder, joint angular waveform of G1 was significantly more in extension over the total GC compared to all older children and adults (p <0.001, G1: -9.5°±7.1; G5: 2.7±7.1, p<0.001). Coronal plane waveforms differed between groups only around TO with an increased ROM in G1-2 (12.9°-13.3°; SD: 4.2°-5.4°) compared to G4-5 (7.6°-9.0°; SD: 2.3°-2.8°, p=0.002). No age-related differences were found in the transverse plane but waveforms of G2-4 differed significantly from G1 and G5 after 30% of the GC.

At the elbow, flexion at IC and the joint angular wave forms over the total GC were significantly higher in the youngest children (G1: 38.7° ± 9.1°) compared to all other groups with significantly higher mean flexion of 43.5° ± 9.9° in G1 compared to all other groups (G2-G5: 35.6°–36.4°; SD: 4.7°-7.2°; p<0.001).

At the wrist, a joint angular waveform in increased dorsiflexion with no changes in ROM was found over the total GC in G1-2 compared to adults and during the last part of stance and swing compared to G3-4 with differences as large as 10° at IC between G1 and G5. A mean ulnar deviation (1.4°-4.4° ; SD: 6.9°-8.5°) was found for G1-G2 and was significantly different from the radial deviation in G4-5 (1.3°-4.0° ; SD: 5.0°-6.1°) for mean joint angle and for the joint angular wave form over the total GC except around TO in adults.

[Table 2 near here]

Age-related changes in consistency (fine-tuning)

Next to a decrease in inter-individual SD over age groups, high inconsistency was observed between different gait cycles of the younger children (intra-individual variation) compared to adults (Figure 1 & 3).

At the *shoulde*r, consistency was low in the transverse plane in all groups (up to 30° in the youngest children) but only significant different between G3-5 at few specific moments in time (Appendix2). Consistency improved from G2 for A-TO and mean joint angle in the coronal plane, from G3 for A-IC, meanjoint angle and ROM in sagittal and ROM in coronal plane and from G4 for time to peak in the coronal plane. In the sagittal plane a small but significant lower consistency was found over the entire gait cycle in G1 compared to all other groups. The lager coronal plane differences in were only significant in swing between G1-2 and G4.

At the *elbow*, consistency improved from G2 for A-IC, from G3 for A-TO, peak value and mean joint angle and in G5 for time to peak. No changes in consistency were observed for ROM but spm1D analysis revealed an significant lower consistency in G1 compared to G2-5 over the entire gait cycle

At the *wris*t, consistency improved from G2 for A-IC, A-TO and mean coronal plane joint angle, from G3 for coronal plane peak value and in G5 for sagittal plane time to peak in. No changes in consistency were found for the other kinematic parameters but spm1D revealed significant differences in joint angular wave forms over the entire gait cycle between G1-2 and G4-5 in both planes.

[Figure 3 near here]

Discussion

This study aimed at gaining insights into maturation and fine-tuning towards an adult-like arm swing pattern and determining the age at which arm movements during typical gait can be considered mature. It is the first to evaluate joint angular waveforms continuously in a large cohort, with a wide age-range, allowing comparison of arm movements between children and adults. Although adult-like arm swing patterns were present in general at the age of three, maturation (change to adult-like values), fine-tuning (improved consistency) or a combination of both was still observed in all joints and planes and was found to be joint and parameter-specific.

The **overall shape** of adult-like patterns, with an increase in joint angle from IC to a single peak value around opposite IC, was already visible in the youngest children. These findings confirm previous literature that by the age of three years the guard position has already changed into arm swinging [1]. However, the older children and adults showed more pronounced patterns, i.e. increased ROM and more consistently timed. Furthermore, in the youngest children, remnants of guard position were observed at the elbow with increased mean flexion angle. Also, an improved consistency for both mean shoulder abduction and mean elbow flexion from the age of ten, respectively fourteen years indicate that it takes until that age before children consistently use adult-like patterns.

For **timing of peak values**, no age-related changes were found. Peak values of arm movement in the different planes occurred around 50% of the gait cycle, coinciding with IC of the opposite foot, indicating that coordination of reciprocal swing between arms and legs is present at the onset of arm swing. Although no maturation effect was found for time to peak for any joint or plane, an improved consistency was observed at the shoulder in the coronal and at the elbow and wrist in the sagittal plane with increasing age until respectively 14 years and 19 years, indicating a long lasting fine tuning of timing. This confirms the findings of Meyns et al. who investigated age-related differences in interlimb coordination in children and adults using a continuous relative phase between limb movements and found gradual changes that lasted until adult ages [19].

The variation in age-related changes in **mean values** and **consistency** between the different parameters warrants a more detailed discussion per joint. This is the first study to include different age groups, but previous authors reported on some specific parameters of arm movements in children that are in agreement. Romkes et al. reported the same parameters, except for mean positions, in 9 children between 8-18 years [14], Galli et al. investigated ROM and A-IC in 20 children (9.2 year; SD: 5.7 year) [15] and Riad et al. only included ROM in 15 adolescents (18.6 year; no SD) [13].

At the *shoulder*, mean joint angle in the sagittal plane evolved from extension in the youngest children (G1-2) to flexion after the age of ten with a ROM similar to previous literature and no difference between age-groups. Mean abduction however, did not show age-related differences though a larger ab-adduction ROM was found for the youngest children (G1-G2) compared to the older children and adults, in line with Galli et al. and Romkes et al. but slightly larger than Riad et al. reported. Mean coronal joint angles were external and not different over age-groups but ROM was significantly smaller in all children compared to adults and larger than observed in the small and variable population of Romkes et al. and Galli et al.. Poor consistency was observed in the youngest children in all three planes, with adult-like consistency from ten years on.

At the *elbow*, a larger mean flexion angle over the gait cycle compared to all other groups was observed for the youngest children (G1) in contrast to the ROM which was largest in adults (23°), compared to all children (16-17°). This ROM is in accordance with Romkes et al. [14] and Zijlmans et al. [7] but smaller than in Riad et al. [13] and Galli et al. [15] who found ROM up to 30° in elbow flexion during walking. These differences between studies are probably caused by differences in methodology.

At the *wrist* a significantly larger mean dorsiflexion and ulnar deviation joint angle was found until the age of ten with no age-related differences in ROM, similar to Romkes et al. [14] and Riad et al. [13].

Regarding **age of maturation and fine-tuning**, no chronological evolution in age-related changes was found over the different joints. Therefore, arm movements were not found to develop or change in either a proximal or distal sequence.

While the positional changes in shoulder and elbow in the sagittal plane are most likely a remnant of the high guard position, it remains unclear why the positional changes at the wrist take place. They may also be part of a fixation pattern.

The higher variations in all joints and planes in the youngest group clearly indicate that the arm movements during gait were far from the consistent pattern seen in the adults.

When walking faster, arm swing amplitude was found to be increased [17]. Therefore, walking speed should be taken into account in both clinical practice and research. In the present study walking speed was normalized to leg length (Froude number) [22] to eliminate effects of difference in height between age groups. However, the Froude number was still significantly different between groups (Table 1). Therefore, in the analysis of age-related differences between parameters, the main effects of the Froude number, were taken into account for further analysis of ROM parameters, as, especially at the shoulder in the sagittal plane regression analysis revealed interaction with walking speed.

This study has some limitations. An initial limitation is that the Plug-in Gait model has not yet been fully validated regarding upper extremity kinematics. Due to the complexity of the shoulder joint it is discussable whether a joint based approach is the most appropriate. Potentially, the model is too simplistic and does not identify the underlying movements correctly [25]. However, as the main goal was to characterize arm swing and not define how it originates in the shoulder we believe it to be fit for the purpose of the study. A next limitation is that, as the shoulder is a joint with three degrees of freedom with rotations close to 90°, we had to deal with gimbal lock. The custom-made software allowed to discover and recover the majority of gimbal lock trials so that only few trials had to be excluded. Nevertheless, we were still able to make five age groups, each including more than 15 participants. The main strength of this study is therefore a large sample size all collected with the same test protocol and equally distributed over a wide age range.
The description of age-related changes should now be validated with longitudinal data. More-over, an even larger sample size per age group would strengthen the findings and extend the framework for use in clinical practice.

In conclusion, although reciprocal arm swing is present, age-related changes in arm movements can be found after the age of 3 years in all joints and planes. A different pace in the observed changes per parameter makes it difficult to conclude on an overall age of maturation, but in general arm movements cannot be considered mature before the age of 10-14 years. Furthermore, a decrease in consistency, defined as fine-tuning, is characteristic for growing children and seems to evolve into adulthood. For clinical practice we therefore recommend not only to use age-related data to take into account age-related patterns and variation, but also to use a sufficient number of trials per patient to allow the evaluation of consistency.

Acknowledgements

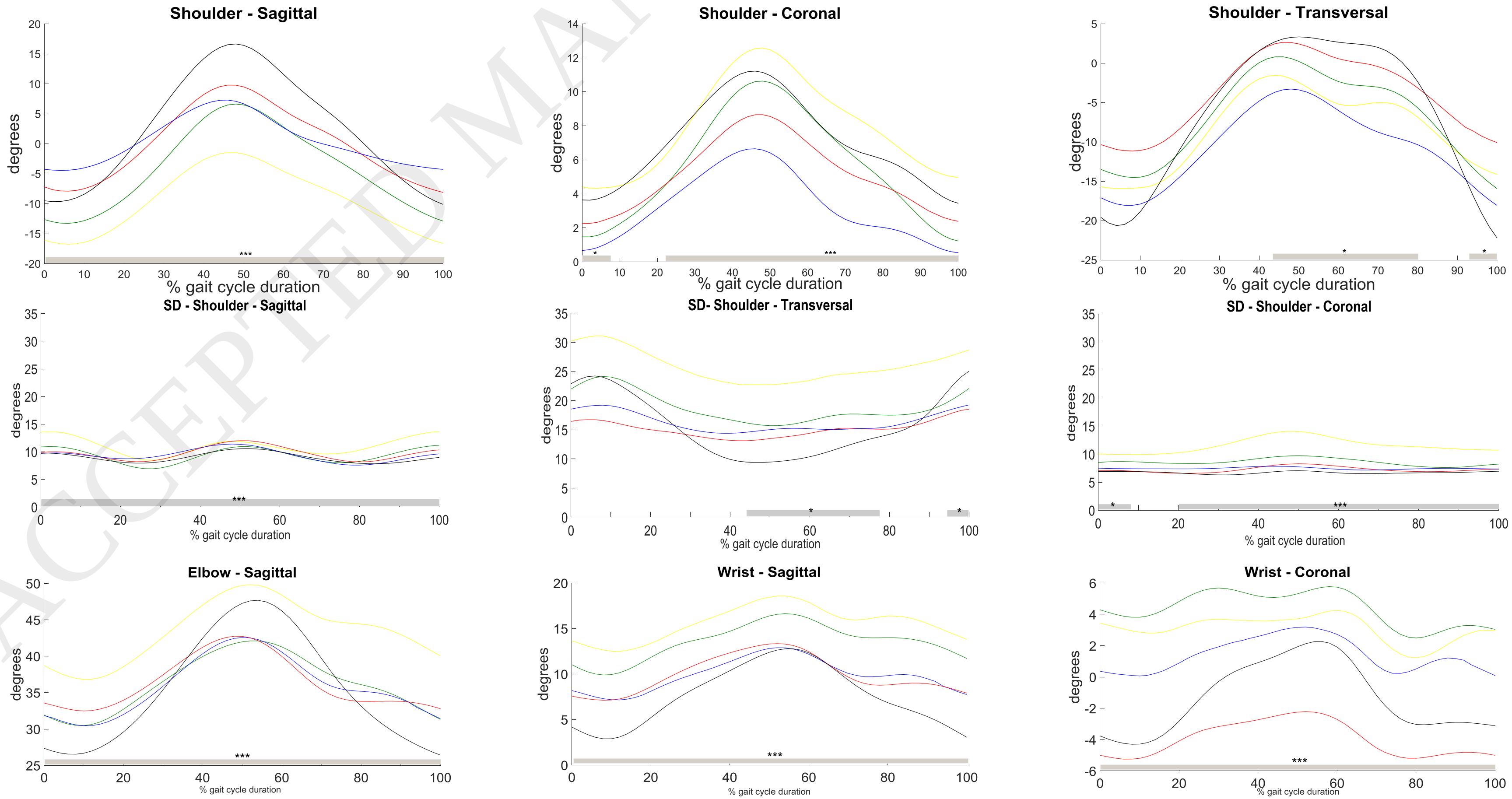
PVdW was supported by a grant from 'Artesis onderzoeksproject G827' UAntwerpen. PM was supported by grants from 'bijzonder onderzoeksfonds' KU Leuven [grant number OT/08/034, PDMK/12/180], and by FWO (Fonds voor Wetenschappelijk Onderzoek Vlaanderen; scientific research funding Flanders) [grant number G.0901.11]. We thank the kinesiologists of the Clinical Motion Analysis Laboratory, CERM, UZ Pellenberg for their assistance and clinical expertise during the measurements. Special thanks are also due to all children and adults for participation.

References

1. Sutherland DH. The development of mature gait. *Gait Posture* 1997;6:163-70.
2. Burnett CN, Johnson EW. Development of gait in childhood. II. *Dev Med Child Neurol* 1971;13(2):207-15.
3. Ledebt A. Changes in arm posture during the early acquisition of walking. *Infant behavior & development* 2000;23:79-89.
4. Huang X, Mahoney JM, Lewis MM, et al. Both coordination and symmetry of arm swing are reduced in Parkinson's disease. *Gait & posture* 2012;35(3):373-7. doi: 10.1016/j.gaitpost.2011.10.180
5. Lewek MD, Poole R, Johnson J, et al. Arm swing magnitude and asymmetry during gait in the early stages of Parkinson's disease. *Gait & posture* 2010;31(2):256-60. doi: 10.1016/j.gaitpost.2009.10.013
6. Stensdotter A, Pedersen N, Wanvik A, et al. Upper body 3-dimensional kinematics during gait in psychotic patients: a pilot-study. *Exp Brain Res* 2012;221(4):393-401. doi: 10.1007/s00221-012-3184-7 [published Online First: 2012/07/24]
7. Zijlmans JC, Poels PJ, Duysens J, et al. Quantitative gait analysis in patients with vascular parkinsonism. *Movement disorders : official journal of the Movement Disorder Society* 1996;11(5):501-8. doi: 10.1002/mds.870110505 [published Online First: 1996/09/01]
8. Meyns P, Bruijn SM, Duysens J. The how and why of arm swing during human walking. *Gait Posture* 2013;38(4):555-62. doi: 10.1016/j.gaitpost.2013.02.006 [published Online First: 2013/03/16]
9. Kuhtz-Buschbeck JP, Brockmann K, Gilster R, et al. Asymmetry of arm-swing not related to handedness. *Gait Posture* 2008;27(3):447-54. doi: 10.1016/j.gaitpost.2007.05.011
10. Plate A, Sedunko D, Pelykh O, et al. Normative data for arm swing asymmetry: how (a)symmetrical are we? *Gait Posture* 2015;41(1):13-8. doi: 10.1016/j.gaitpost.2014.07.011
11. Wagenaar RC, R.E.A. VE. Dynamics of pathological gait. *Human Movement Sciences* 1994;13:441-71.
12. Goudriaan M, Jonkers I, van Dieen JH, et al. Arm swing in human walking: What is their drive? *Gait Posture* 2014 doi: 10.1016/j.gaitpost.2014.04.204 [published Online First: 2014/05/29]
13. Riad J, Coleman S, Lundh D, et al. Arm posture score and arm movement during walking: a comprehensive assessment in spastic hemiplegic cerebral palsy. *Gait Posture* 2011;33(1):48-53. doi: 10.1016/j.gaitpost.2010.09.022
14. Romkes J, Peeters W, Oosterom AM, et al. Evaluating upper body movements during gait in healthy children and children with diplegic cerebral palsy. *J Pediatr Orthop B* 2007;16(3):175-80.
15. Galli M, Cimolin V, Albertini G, et al. Kinematic analysis of upper limb during walking in diplegic children with Cerebral Palsy. *European journal of paediatric neurology : EJPN : official journal of the European Paediatric Neurology Society* 2014;18(2):134-9. doi: 10.1016/j.ejpn.2013.09.007 [published Online First: 2013/10/26]
16. Hejrati B, Chesebrough S, Bo Foreman K, et al. Comprehensive quantitative investigation of arm swing during walking at various speed and surface slope conditions. *Human movement science* 2016;49:104-15. doi: 10.1016/j.humov.2016.06.001

17. Meyns P, Van Gestel L, Massaad F, et al. Arm swing during walking at different speeds in children with Cerebral Palsy and typically developing children. *Research in developmental disabilities* 2011;32(5):1957-64.
18. Van de Walle P, Desloovere K, Truijen S, et al. Age-related changes in mechanical and metabolic energy during typical gait. *Gait Posture* 2010;31(4):495-501. doi: 10.1016/j.gaitpost.2010.02.008
19. Meyns P, Molenaers G, Desloovere K, et al. Interlimb coordination during forward walking is largely preserved in backward walking in children with cerebral palsy. *Clin Neurophysiol* 2014;125(3):552-61. doi: 10.1016/j.clinph.2013.08.022
20. Meyns P, Desloovere K, Molenaers G, et al. Interlimb coordination during forward and backward walking in primary school-aged children. *PLoS One* 2013;8(4):e62747. doi: 10.1371/journal.pone.0062747
21. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res* 1990;8(3):383-92.
22. Hof AL, Zijlstra W. Comment on "Normalization of temporal-distance parameters in pediatric gait". *J Biomech* 1997;30(3):299, 301-2.
23. Pataky TC, Vanrenterghem J, Robinson MA. The probability of false positives in zero-dimensional analyses of one-dimensional kinematic, force and EMG trajectories. *J Biomech* 2016;49(9):1468-76. doi: 10.1016/j.jbiomech.2016.03.032
24. Pataky TC, Robinson MA, Vanrenterghem J. Region-of-interest analyses of one-dimensional biomechanical trajectories: bridging 0D and 1D theory, augmenting statistical power. *PeerJ* 2016;4:e2652. doi: 10.7717/peerj.2652
25. Doorenbosch CA, Harlaar J, Veeger DH. The globe system: an unambiguous description of shoulder positions in daily life movements. *J Rehabil Res Dev* 2003;40(2):147-55.

Figure 1: Group average and group standard deviation (SD) of the joint angular time profiles over the gait cycle in sagittal (shoulder, elbow, wrist), transversal (shoulder) and coronal plane (shoulder and wrist)
sagittal plane (+= flexion), coronal plane (+= abduction) and transversal plane (+= internal rotation); x-as: percentage of the gait cycle; y-as: joint angles (°)
black line (adults – G5); blue line (adolescents – G4); red line (pubertal children – G3), green line (children – G2); yellow line (young children – G1)
significant differences between age groups (SPM-d1; ANOVA) are presented by a grey rectangle: * p<0.05, ** p<0.01, *** p<0.001



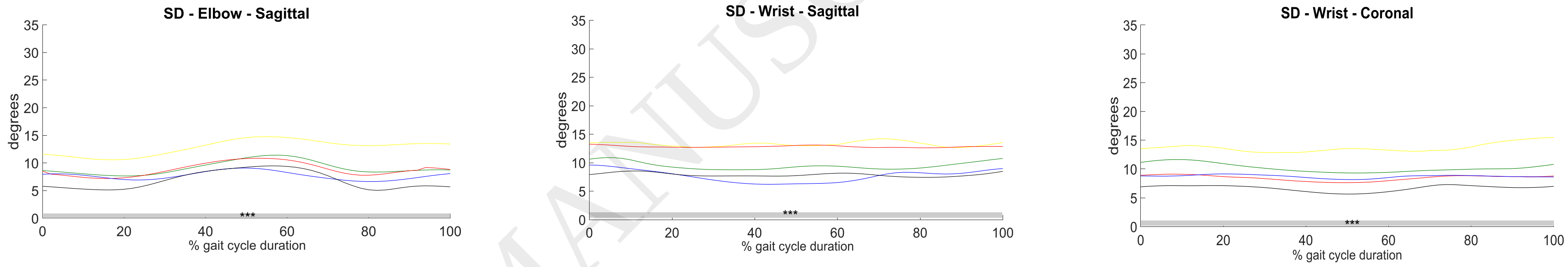
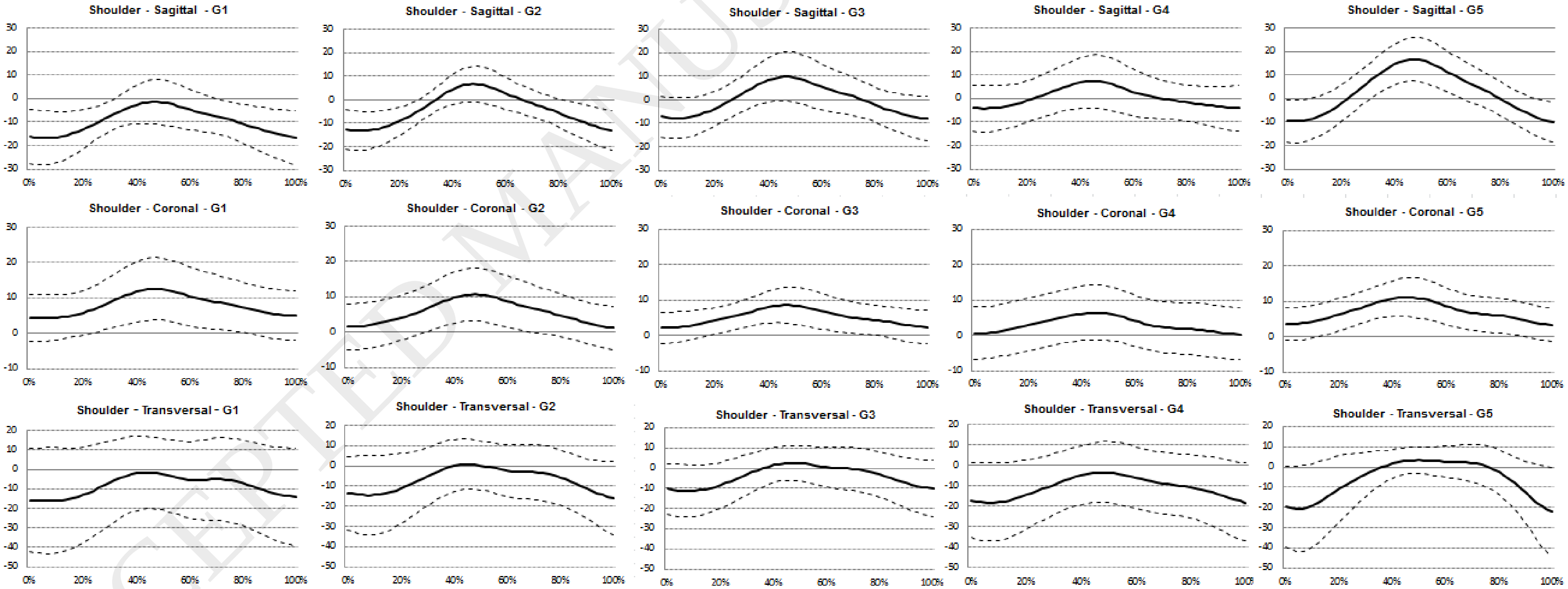


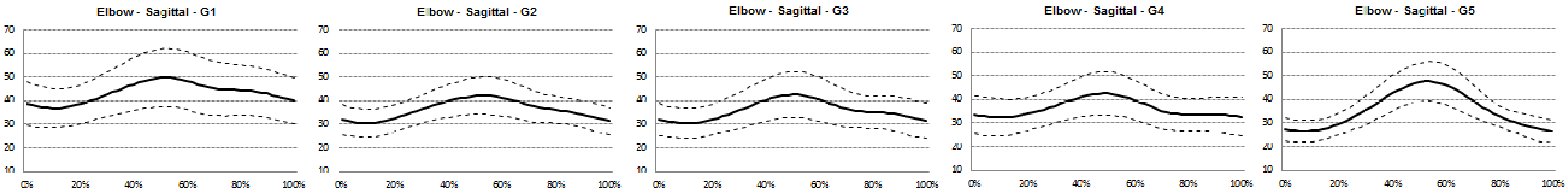
Figure 2 Mean (—) and one standard deviation (---) of the joint angles over the total gait cycle of the shoulder in the sagittal, coronal and transversal plane (A), the elbow in the sagittal plane (B) and the wrist in the sagittal and coronal plane over the gait for all age groups (young children (G1); 3.0-5.9 years, children (G2); 6.0-9.9 years, n=24, pubertal children (G3); 10.0-13.9 years, adolescents (G4); 14.0-18.9 years and adults (G5); 19.0-35.2 years).

sagittal plane (+= flexion), coronal plane (+= abduction) and transversal plane (+= internal rotation); x-as: percentage of the gait cycle ; y-as: joint angles (°)

A


Shoulder - Sagittal - G1
Shoulder - Sagittal - G2
Shoulder - Sagittal - G3
Shoulder - Sagittal - G4
Shoulder - Sagittal - G5
Shoulder - Coronal - G1
Shoulder - Coronal - G2
Shoulder - Coronal - G3
Shoulder - Coronal - G4
Shoulder - Coronal - G5
Shoulder - Transversal - G1
Shoulder - Transversal - G2
Shoulder - Transversal - G3
Shoulder - Transversal - G4
Shoulder - Transversal - G5

B


Elbow - Sagittal - G1
Elbow - Sagittal - G2
Elbow - Sagittal - G3
Elbow - Sagittal - G4
Elbow - Sagittal - G5

C

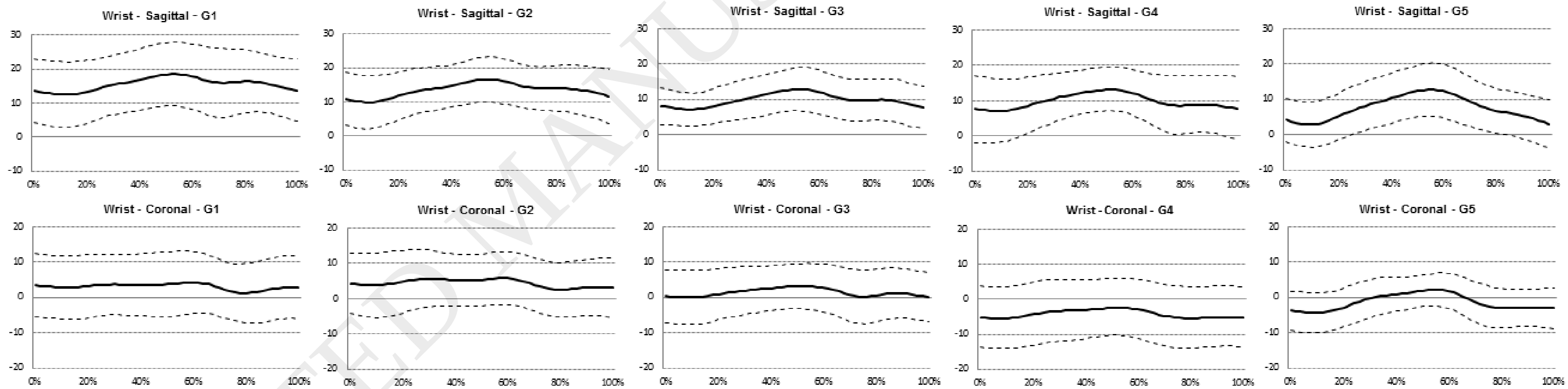

Wrist - Sagittal - G1
Wrist - Sagittal - G2
Wrist - Sagittal - G3
Wrist - Sagittal - G4
Wrist - Sagittal - G5
Wrist - Coronal - G1
Wrist - Coronal - G2
Wrist - Coronal - G3
Wrist - Coronal - G4
Wrist - Coronal - G5
30
20
10
0
-10
-20
0%
20%
40%
60%
80%
100%

Figure 3: Joint angular consistency plots of a 3 year old child (A) and of a 22 year adult (B) along with group average (dotted line).

+= flexion; x-as: percentage of the gait cycle; y-as: joint angles (°)

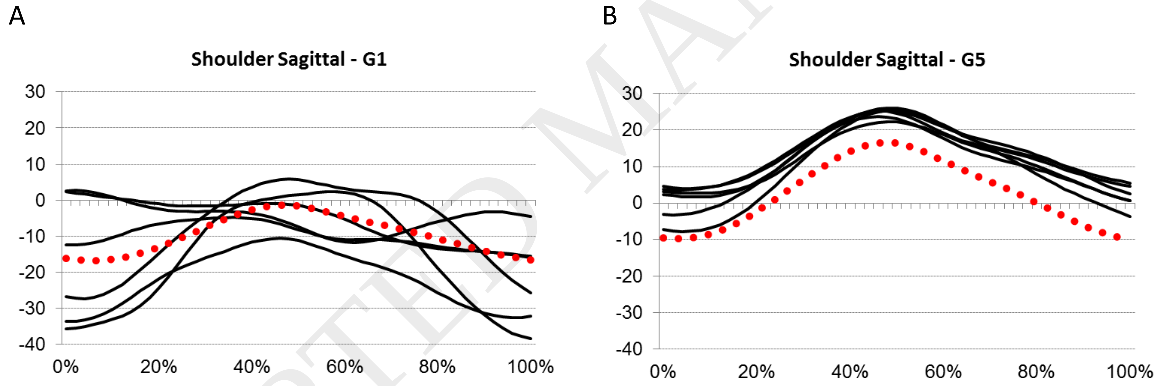


Table 1 : Patients characteristics

Number of participants (male/female) per age-group (G); mean and standard deviation per age-group for age, body weight, height, walking speed and Froude number

	Group 1 3.0-5.9 y	Group 2 6.0-9.9 y	Group 3 10.0-13.9 y	Group 4 14.0-18.9y	Group 5 19.0-35.2y	P-value
Number of participants (male/female)	20 (8/12)	24 (8/16)	26 (15/11)	16 (8/8)	16 (6/10)	-
Age (years)	4.6 ± 0.9	7.7 ± 1.0	11.5 ± 0.9	16.1 ± 1.1	26.4 ± 3.9	-
Body weight (kg)	17.1 ± 2.7	25.5 ± 4.6	39.3 ± 7.4	59.4 ± 9.5	67.1 ± 9.9	-
Height (m)	1.07 ± 0.08	1.28 ± 0.08	1.52 ± 0.09	1.72 ± 0.09	1.73 ± 0.08	-
Walking speed (m/s)	1.05 ± 0.16	1.21 ± 0.17	1.28 ± 0.15	1.25 ± 0.14	1.36 ± 0.10	<0.001[a]
Froude number	0.47 ± 0.07	0.49 ± 0.07	0.46 ± 0.05	0.42 ± 0.04	0.46 ± 0.04	<0.001[b]

[a] Post Hoc Tukey HSD showed significant differences between G1-4&G5, G2-G3&G5, G3-G5
[b] Post Hoc Tukey HSD showed significant differences between G1&G3-G4, G2&G3-G5, G3-G4, G4-G5

A			G1	G2	G3	G4	G5	**p value**	**Pairwise comparisons (p<0.05)**
			Mean value ± SD *Mean consistency ± SD*					Value *Consistency*	
Shoulder	**Sagittal** Flexion (+) Extension (-)	Angle at IC (°)	-16.1±11.4	-12.6 ±8.3	-7.2 ±8.5	-4.3±8.0	-9.5 ±9.1	**0.012**	G1-G3-4; G2-G4
			7.4±3.9	*7.1±3.5*	*5.1±2.7*	*5.0±3.8*	*4.0±2.2*	***0.010***	*G1-2-G5;G1-G3*
		Angle at TO (°)	-4.1 ±8.9	3.8 ±7.1	6.0 ±9.8	2.3±8.5	11.2 ±8.9	**<0.001**	G1-G2-5; G2-G5; G4-G5
			7.0±3.1	*7.5±3.7*	*5.3±2.7*	*5.1±3.0*	*4.7±3.0*	*0.076*	
		Peak value (°)	2.2±8.9	8.1 ±6.7	11.0 ±10.3	9.0±8.2	16.9 ±9.3	**<0.001**	G1-G2-5;G2-4-G5
			6.6±2.5	*7.1±3.5*	*4.9 ±2.3*	*5.3±8.2*	*5.0 ±3.0*	*0.124*	
		Time to peak (%GC)	47.6 ± 6.1	48.0 ±5.7	46.1 ±4.5	45.5±5.2	47.1 ±1.7	0.376	
			10.6±14.4	*9.3±9.8*	*8.6±11.0*	9.1±12.6	*1.5±0.7*	0.594	
		Mean position (°)	-9.5 ±7.1	-4.1 ±5.1	0.0 ±7.2	0.4±7.6	2.7 ±7.4	**<0.001**	G1-G2-5, G2-G3&5
			5.0 ±2.1	*4.4 ±1.8*	*2.9 ±1.3*	*3.4±1.7*	*2.7 ±2.1*	***<0.001***	*G1-2-G3&5; G1-G4*
		ROM over GC (°)	24.1 ±9.1	24.7 ±10.5	21.9 ±12.4	16.4±7.2	27.9 ±9.8	0.169	
			9.1 ±5.1	*10.5 ±6.7*	*5.2 ±3.3*	*5.2±4.5*	*6.6±3.3*	***0.040***	*G1-G4; G2-G3-5*
	Coronal Abduction (+) Adduction (-)	Angle at IC (°)	4.4 ±6.5	1.5 ±6.4	2.3 ±4.4	0.7±6.0	3.6±4.7	0.245	
			6.8±5.0	*5.7±2.6*	*5.3±3.2*	*4.1±3.1*	*4.1±4.0*	*0.166*	
		Angle at TO (°)	10.9±8.4	9.3 ±7.4	7.2 ±5.3	4.1±6.0	8.7±5.2	0.059	
			8.9±6.9	*5.6±3.6*	*5.8±3.3*	*3.7±3.2*	*3.8±2.9*	***0.003***	*G1-G2-5*
		Peak value (°)	14.6±7.5	11.9 ±7.2	10.2 ±5.3	7.2±6.4	11.7±5.4	**0.034**	G1-G3-4
			8.0±6.1	*5.3 ±3.0*	*5.8 ±2.9*	*3.9±3.6*	*3.9±3.2*	***0.011***	*G1-G2,4&5*
		Time to peak (%GC)	48.6±6.7	48.0 ±9.0	46.6 ±7.4	42.1±6.7	43.9±5.1	0.098	
			12.8±11.8	*14.9±9.8*	*16.4±11.4*	*8.2±7.2*	*5.3±5.2*	***0.020***	*G1-3-G5*
		Mean position (°)	8.0±7.1	5.7 ± 6.3	5.2 ±4.1	3.3±5.9	7.1±4.8	0.144	
			7.3±6.1	*4.5 ± 3.1*	*5.0 ±3.0*	*5.0 ±3.0*	*3.4±3.5*	***0.032***	*G1-G2,4&5*
		ROM over GC (°)	13.3±4.2	12.9 ±5.4	10.0 ±3.9	7.6±2.3	9.0±2.8	**0.002**	G1-G3-5, G2-G4-5
			5.1±2.7	*4.8±2.7*	*3.6±2.2*	*2.1±1.0*	*2.2±0.7*	***<0.001***	*G1-G3-5, G2-G4-5*
	Transversal Internal (+) External (-)	Angle at IC (°)	-15.7 ±26.4	-13.5 ±18.0	-10.3 ± 12.6	-17.1±16.3	-19.6±20.0	0.479	,
			14.4±9.7	*13.0±6.1*	*10.8±4.6*	*9.4±4.5*	*11.1±7.3*	0.233	
		Angle at TO (°)	-4.9 ±19.2	-1.9 ±12.4	0.6 ± 9.8	-6.5±10.6	2.6±7.7	0.281	
			12.2±9.1	*10.4±5.5*	*10.5±5.1*	*10.1±7.4*	*7.1±3.9*	0.363	
		Peak value (°)	3.0 ±22.8	4.4 ±12.7	5.8 ± 10.1	-1.3±9.6	6.7±10.0	0.527	
			11.7 ±8.4	*10.6 ±5.9*	*9.7 ± 5.3*	*8.0±5.2*	*8.1±6.5*	0.275	
		Time to peak (%GC)	48.6±9.4	49.6 ±8.0	51.5 ± 12.9	52.3±5.0	53.2±7.6	0.590	
			18.4±9.9	*18.8±8.3*	*16.2±10.0*	*15.3±9.7*	*10.1±11.0*	*0.225*	
		Mean position (°)	-8.4 ±22.0	-6.8 ±14.5	-4.0 ± 10.4	-10.7±12.6	-6.1±11.0	0.602	
			11.0±7.9	*9.8 ± 5.0*	*9.1 ±4.9*	*7.7±5.7*	*7.6±5.2*	*0.354*	
		ROM over GC (°)	25.9 ±11.8	26.5 ±10.4	22.4 ± 7.8	21.2±11.4	32.4±19.8	**0.111**	
			7.3 ± 3.9	*10.3 ±5.7*	*8.3 ± 3.6*	*8.1±4.7*	*10.1±6.9*	**0.861**	

B			G1	G2	G3	G4	G5	p value	Pairwise comparisons (p<0.05)
					Mean value ± SD *Mean consistency ± SD*				Value *Consistency*
Elbow	Sagittal Flexion (+) Extension (-)	Angle at IC (°)	38.7±9.1 *6.5±4.8*	31.9±6.2 *5.8±3.4*	31.8±6.9 *5.1±2.4*	33.6±5.4 *5.8±3.1*	27.4±4.9 *3.5±1.5*	**<0.001** ***0.040***	G1-G2-5; G2-G5, G3-G5;G4-G5 *G1-G5*
		Angle at TO (°)	48.8 ± 12.4 *8.2±4.6*	41.8± 8.0 *8.1±4.6*	40.9 ± 9.3 *5.1±2.3*	39.4 ± 6.9 *3.8±2.0*	46.0 ± 8.4 *4.5±1.8*	**0.008** ***<0.001***	G1-G2-4 *G1-G3&5, G2-G5*
		Peak value (°)	52.4± 12.4 *8.0±4.8*	44.8 ± 8.0 *8.3 ± 4.7*	44.5 ± 9.3 *5.2 ± 1.8*	45.1 ± 6.1 *5.5± 2.0*	48.6 ± 8.7 *4.8 ± 2.4*	**0.037** ***0.015***	G1-G2-3 *G1&2-G3&5*
		Time to Peak (%GC)	56.5 ± 10.4 *16.3±11.1*	51.8 ± 8.1 *15.7±9.6*	52.9 ± 7.3 *15.2±10.6*	48.3 ± 8.1 *14.5±13.0*	52.5 ± 3.6 *3.5±2.0*	0.075 *0.028*	 *G1-4-G5*
		Mean position (°)	43.5 ±6.0 *4.7 ±9.9*	36.3 ± 5.8 *4.9 ± 2.8*	35.9 ± 7.2 *3.0 ± 1.5*	36.4 ± 4.7 *3.8 ± 2.0*	35.6 ± 4.7 *2.4 ± 1.9*	**0.002** ***0.001***	G1-G2-5 *G1-G3&5; G2-G5*
		ROM over GC (°)	17.3 ± 6.9 *7.3±3.9*	16.5 ± 6.1 *8.6±4.4*	16.6 ± 6.2 *5.5±3.1*	15.7 ± 6.2 *5.5±2.9*	23.0± 9.7 *5.2±1.7*	**0.012** *0.053*	G1-4-G5

C			G1	G2	G3	G4	G5	p value	Pairwise comparisons (p<0.05)
					Mean value ± SD *Mean consistency ± SD*				Value *Consistency*
Wrist	Sagittal Dorsiflexion (+) Palmar flexion (-)	Angle at IC (°)	13.7 ± 9.4 *8.8±6.4*	11.0 ± 7.7 *7.0±4.2*	8.2 ± 5.3 *7.1±11.5*	7.6 ± 6.6 *6.1±4.9*	4.2 ± 6.2 *4.9±2.6*	**0.006** 0.593	G1-G3-5; G2-G5
		Angle at TO (°)	18.2 ± 9.7 8.4±5.8	16.4 ± 6.7 6.2±4.1	12.4 ± 6.3 6.5±10.9	12.1 ± 4.6 4.9±2.5	12.2 ± 7.8 3.3±1.8	0.123 0.873	
		Peak value (°)	21.2 ± 8.6 *8.1±5.9*	19.0 ± 7.2 *6.2±3.8*	14.5 ± 5.8 *6.6±11.2*	14.2 ± 4.4 *4.4±1.9*	13.2 ± 7.5 *3.1±1.8*	**0.010** *0.187*	G1-G3-5; G2-G5
		Time to Peak (%GC)	54.5 ± 11.1 *22.6±8.6*	53.7 ± 10.2 *21.0±9.0*	52.5 ± 6.8 *21.2±11.8*	50.9 ± 8.6 *12.5±9.6*	53.9 ± 2.7 *4.4±3.1*	0.832 **<0.001**	 G1-4-G5
		Mean position (°)	16.6 ± 9.1 7.9±6.3	13.5 ± 6.7 5.1±3.8	9.9 ± 5.4 5.9±11.0	10.0 ± 5.3 4.7±2.9	7.6 ± 6.5 3.4±2.2	**0.012** *0.781*	G1-G3&5;G2-G5
		ROM over GC (°)	11.8 ± 5.6 *4.6±2.1*	11.7 ± 5.1 *5.3±3.0*	9.8 ± 3.1 *4.9±3.0*	8.9 ± 5.3 *4.6±4.2*	11.6 ± 6.5 *4.4±3.8*	**0.005** *0.890*	
	Coronal Ulnar deviation (+) Radial deviation (-)	Angle at IC (°)	3.5 ± 8.9 *9.2±6.6*	4.3 ± 8.4 *7.1±3.9*	0.4 ± 7.4 *5.1±2.4*	-5.0 ± 6.2 *6.1±3.6*	-3.8 ± 5.5 *4.3±4.0*	**0.001** ***0.008***	G1-2-G4-5; G3-G4 G1-G3&5
		Angle at TO (°)	4.1 ± 8.8 9.1±6.4	5.8 ± 7.4 5.9±2.6	2.9 ± 6.8 4.2±2.0	-3.0 ± 6.0 5.8±3.6	1.9 ± 4.9 3.5±2.2	**0.010** ***<0.001***	G1-3-G4 G1-G2-3&5
		Peak value (°)	8.9 ± 9.1	9.5 ± 8.3	6.1 ± 7.0	-0.5 ± 5.9	3.3 ± 5.0	**0.004**	G1-2-G4-5; G3-G4

		8.9±6.5	*6.3±2.9*	*4.6±1.9*	*3.1±1.8*	*3.8±2.1*	***<0.001***	G1-G2-5; G2-G5
	Time to Peak (%GC)	46.5 ± 14.2	46.2 ± 10.7	46.8 ± 11.2	47.2 ± 12.0	49.9 ± 7.8	0.686	
		29.7±9.1	*27.6±9.0*	*24.2±10.4*	*20.0±12.5*	*8.5±6.8*	*0.606*	
	Mean position (°)	3.1 ± 8.5	4.4 ± 7.8	1.4 ± 6.9	-4.0 ± 6.1	-1.3 ±5.0	**0.007**	G1-G4; G2-G4-5, G3-G4
		8.7±6.7	5.5±2.9	4.1±2.1	5.8±3.2	3.5±2.4	***<0.001***	G1-G2-2&5
	ROM over GC (°)	11.3 ± 4.7	10.5 ± 4.5	9.6 ± 2.9	6.7 ± 2.5	8.8 ± 3.9	0.426	
		6.2±6.9	*4.5±1.9*	*3.6±1.5*	*2.8±1.7*	*3.2±2.0*	0.027	*G1-G3-5*

Table 2 Mean values and mean consistency of the kinematics of the shoulder (A), elbow (B) and wrist (C) for the five age groups: young children (G1), children (G2), pubertal children (G3), adolescents (G4), adults (G5) .

Shaded cases indicate that a mean values are significantly different from adult values (G5). A lighter shade of grey indicates that the intermediate groups differ both from the younger and older age groups, suggesting that maturation follows a stepwise process. Borders indicate that consistency is significantly larger than in adults (G5).