Chapter 4

Gait analysis in children with cerebral palsy via inertial and magnetic sensors: a validation study

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Submitted

4.1 Abstract

Gait analysis is used to assess gait deviations in children with cerebral palsy (CP). However, 3D kinematic measurement by means of optoelectronic systems can only be performed in gait laboratories. Alternatively, an inertial and magnetic measurement system (IMMS) can be applied for ambulatory motion-tracking of body segments. A protocol named Outwalk has recently been developed to measure the 3D kinematics during gait by means of IMMS. This study validated the application of IMMS, based on the Outwalk protocol, in gait analysis of six children with CP and one typically developing child. Reference joint kinematics were simultaneously obtained from a laboratory-based system and protocol. On average, the root mean square error (RMSE) of Outwalk/IMMS, compared to the reference, was less than 17^{o} in the transverse plane, and less than 10^{o} in the sagittal and frontal planes. Range of motion differences were less than 3^{o}. The greatest differences were found in offsets in the knee rotation (6 ± 14^{o}) and ankle rotation (7 ± 9^{o}), and in the hip flexion (6 ± 7^{o}). These offset differences were mainly caused by a different anatomical calibration in the protocols. When removing the offsets, RMSE was always less than 4^{o}. As such, the IMMS is suitable for clinical gait analysis in a laboratory-free setting. However, to improve the accuracy of joint kinematic measurements, further studies should focus on the improvement of anatomical calibrations of the IMMS that can be performed in children with CP.

4.2 Introduction

Cerebral palsy (CP) is the most common cause of motor disability in childhood [1-3]. In clinical practice, gait analysis is performed to assess gait deviations in patients with CP. Conventionally, the measurement of joint kinematics is performed by means of optoelectronic marker systems in gait laboratories [4]. Different protocols have been developed for anatomical calibration of the optoelectronic systems, e.g. the Calibration Anatomical System Technique [5] (CAST), which is based on technical clusters of markers attached to body segments, anatomically calibrated by palpation of bony landmarks. Although optoelectronic-based movement analysis is accurate [6], its use in clinical practice is limited, due to its complexity, costs, and lack of availability of well-equipped gait laboratories. Optoelectronic systems are barely portable, and only a small number of steps can be recorded, due to a measurement volume that is restricted by camera positioning and line of sight problems, resulting in missing data. Moreover, patients adapt their gait pattern, due to the limited space in the laboratory and the feeling that they are being observed [7,8].

Recently, inertial and magnetic measurement systems (IMMSs) have been applied for ambulatory measure of 3D body segment orientations [9-13]. The IMMS has the potential to overcome the limitations of laboratory-based optoelectronic systems. It consists of small, lightweight sensor units comprising miniaturized 3D accelerometers, gyroscopes, and magnetometers [9,14]. Through sensor fusion algorithms, the 3D orientation of each sensor unit is measured with respect to a global, earth-based coordinate system (CS) [15,16]. With the IMMS kinematics can be measured in a laboratory-free setting. Hence, gait analysis can be improved by measurement of a large number of consecutive gait cycles during spontaneous walking.

When a sensor unit of the IMMS is attached to a body segment, anatomical segment orientation must be obtained from the definition of an anatomical CS with respect to the sensor CS. Anatomical calibration of the IMMS can be based on functional movements, static reference postures, and/or careful alignment of sensor units with anatomical structures. A protocol has been proposed for the application of the IMMS in gait analysis [11]. This protocol, called Outwalk, was developed for use in clinical practice. Outwalk has been validated with respect to the CAST protocol in healthy subjects [17] and in transtibial amputees [18], however it has not been assessed in children with CP.

The aim of this study was to validate the application of IMMS, based on the Outwalk protocol, for gait analysis in children with CP. Reference joint kinematics were simultaneously obtained from the conventional laboratory-based optoelectronic system and the CAST protocol. We hypothesized that the differences in joint kinematics would be similar to the differences that have been reported in a previous study in which the IMMS was applied in healthy adults [17].

4.3 Methods

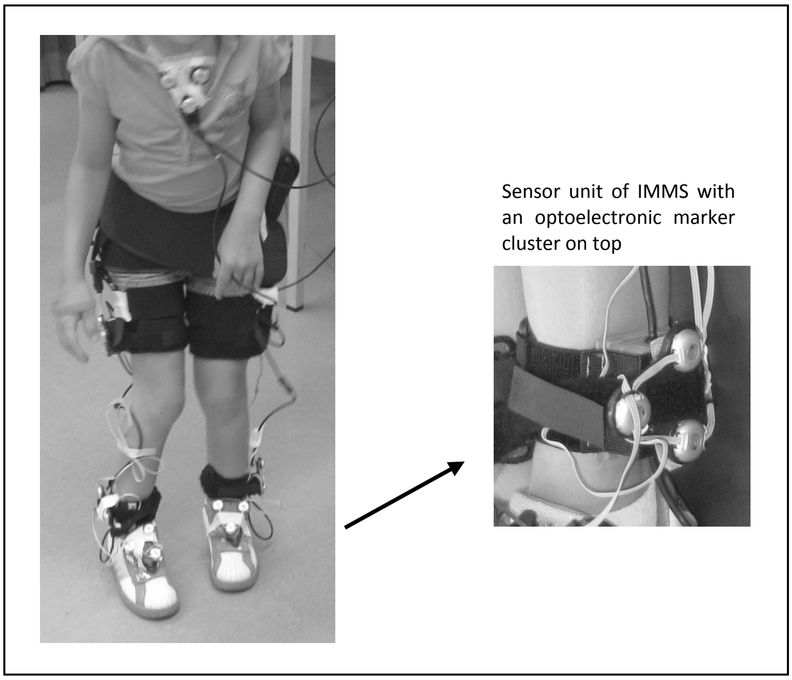
4.3.1 Subjects

Seven children participated in the study: six children with spastic CP (all girls, four with GMFCS I, and two with GMFCS II [19], age 11.6±1.7 years (mean ± standard deviation (SD)), body mass 42.2±11.2 kg, body height 1.50±0.15 m), and one typically developing child (boy, age 12 years, body mass 39 kg, body height 1.64 m). The children with CP were recruited from the Department of Rehabilitation Medicine of the VU University Medical Center in Amsterdam, the Netherlands. The study was approved by the Medical Ethics Committee of the VU University Medical Center. Informed consent was obtained from all parents and children over 12 years of age.

4.3.2 Procedure

Gait measurements of the children were performed in a gait laboratory. The children walked on a 10 metre walkway at comfortable walking speed. Kinematic data were simultaneously measured with the IMMS and an optoelectronic marker system. Sensor units (SUs) of the IMMS (MTx, Xsens Technologies, the Netherlands) were attached to the feet, shanks, thighs, and pelvis with customized elastic straps (Xsens Technologies). The SU on the thorax was attached using skin-friendly double-sided tape. The SUs were positioned according to the Outwalk protocol [11]. In addition, optoelectronic marker clusters (OptoTrak 3020, Northern Digital Instruments, Waterloo, Canada) were rigidly attached to the SUs with double-sided tape (Figure 4.1).

For the computation of joint kinematics, anatomical calibration of the optoelectronic system was according to the CAST protocol [4]. This included the calibration of bony landmarks relative to the marker clusters. A reference measurement was also performed in a static upright posture. The anatomical calibration of the IMMS was according to the



Sensor unit of IMMS with an optoelectronic marker cluster on top

Figure 4.1. A child with cerebral palsy wearing the IMMS sensor units (MTx, Xsens Technologies, the Netherlands) and marker clusters of the optoelectronic system (Optotrak 3020, Northern Digital Instruments, Waterloo, Canada)

Outwalk protocol [11], which includes a static posture in either upright or supine position, and a passive knee flexion/extension movement, imposed by the examiner, to define the functional knee axis. In this study, the static posture and calibration movements were performed in an upright position.

Data-acquisition with the IMMS and the optoelectronic marker system was synchronized using the synchronization pulse from the OptoTrak system (analog signal) recorded in the IMMS. Data were collected at a sample frequency of 100 Hz. Data on at least 5 successful gait trials were collected for each child.

4.3.3 Data analysis

The reference system data were processed in BodyMech (www.BodyMech.nl, custom-made software based on MATLAB (R2009b, the Mathworks)) to obtain joint kinematics. The outcomes are further referred to as CO (i.e. CAST/Optoelectronic).

IMMS data were processed in MATLAB software, based on the MT Software Development Kit (Xsens Technologies) [11]. The orientations of the SUs on the foot, shank and thigh were calculated with the Kinematic Coupling algorithm (KiC [20]), to avoid any influence of a non-homogenous earth magnetic field in the gait laboratory, that could be caused by ferromagnetic materials in the surroundings [21]. The anatomical CSs were defined according to the Outwalk protocol. The outcomes are further referred to as OI (i.e. Outwalk/IMMS).

For three children, the optoelectronic data were also processed according to the Outwalk protocol, and the outcomes are further referred to as OO (i.e. Outwalk/Optoelectronic).

The joint kinematics (3D ankle, knee, and hip angles) of the gait cycles of all successful trials per child were averaged. The differences in kinematics (averaged over the gait cycles) of OI versus CO were assessed. Additionally, the difference between OO and CO was assessed. In this way, differences generated by the protocols (Outwalk and CAST) could be isolated from the differences generated by the systems (IMMS and Optoelectronic) [17].

Parameters used in the evaluation of the joint kinematics were: (i) the difference in range of motion, dROM (ROM: maximal minus minimal joint angle), (ii) the offset (i.e. mean constant difference over the entire gait cycle), (iii) the maximal difference, (iv) the root mean square error (RMSE), and (v) the RMSE with the offset removed (RMSE-offset), expressed in degrees (mean and SD over all children). The mean difference was also expressed as a percentage of the SD of the CO trials (% SD-CO). A difference of more than 100% SD-CO means that the difference between OI and CO is greater than the intra-subject variability of CO.

4.4 Results

Figure 4.2 presents an example of the OI (solid orange lines) and CO (dashed blue lines) kinematics during gait of a child with CP. The ankle, knee and hip kinematics of ten gait cycles of both legs are shown. Differences in OI versus CO are mainly present as offsets.

The differences in OI versus CO kinematics of all children are shown in the box and whisker plots in Figure 4.3. Table 4.1 presents the mean dROM, offset, maximal difference, RMSE and RMSE-offset (averaged over all the children), the SD of the mean, and the mean expressed as a percentage of the SD of the CO trials (i.e. the intra-subject variability). On average, the differences in ROM were less than 3° (SD less than 5°). For the knee and ankle angle in the frontal plane, the dROM was greater than the intra-subject variability of the CO (i.e. the SD-CO was more than 100%).

The transverse plane angles were mainly affected by offsets, i.e. a constant difference over the entire gait cycle. The OI measured on average less external knee rotation and more external ankle rotation (Table 4.1). However, the inter-subject variability was high, as appears from the SDs. In 5 of the 7 children, less hip flexion was measured with the OI than with the CO. The offsets appeared to be greater than the SD of the CO (i.e. SD-CO>100%), except for the hip angle in the transverse plane and the knee angle in the sagittal plane. The large SDs of the offsets demonstrate a high variability in the mean difference between OI and CO, especially in the transverse plane (see also Figure 4.3 and Table 4.1).

Table 4.1. The dROM, offset, maximal difference, RMSE and RMSE-offset for Outwalk/IMMS versus CAST/Optoelectronic of the hip, knee and ankle joint angles of the gait cycle of 7 subjects

Outwalk/IMMS versus CAST/Optoelectronic

	dROM [°]		**offset [°]**		**md.**	**RMSE [°]**		**RMSE-offset [°]**	
	mean±SD	*% SD-CO*	*mean±SD*	*% SD-CO*	*[°]*	*mean±SD*	*% SD-CO*	*mean±SD*	*% SD-CO*
Hip									
flex/ext	-0.4±3.1	14%	-6.4±7.2	211%	18	8.76±4.12	287%	1.94±0.85	64%
add/abd	-0.9±2.2	53%	-1.8±1.5	110%	14	6.46±3.54	399%	1.28±0.30	79%
endo/exo	-0.1±1.6	3%	2.1±6.0	97%	37	13.8±8.59	638%	1.65±0.68	76%
Knee									
flex/ext	-1.4±2.3	30%	-1.8±4.3	37%	12	6.25±2.02	130%	2.09±0.58	44%
var/val	2.4±3.4	152%	-2.6±4.8	168%	26	9.20±6.01	595%	3.62±2.28	234%
endo/exo	-0.1±4.2	5%	6.51±3.5	241%	46	16.1±9.81	593%	3.52±1.44	130%
Ankle									
dors/plant	-0.8±1.5	29%	-3.1±4.3	116%	15	4.59±3.40	172%	1.07±0.38	40%
inv/ev	1.9±1.3	108%	-4.3±2.1	247%	13	5.96±1.05	345%	1.75±0.59	102%
endo/exo	0.2±1.7	13%	-6.6±8.7	382%	27	11.2±2.51	642%	0.97±0.38	56%

SD = Standard Deviation; CO = CAST/Optoelectronic; OI = Outwalk/IMMS
dROM = difference in range of motion; offset = mean constant difference; md. = maximal difference
RMSE = root mean square error; % SD-CO = the mean value as a percentage of the SD of the CO trials
A positive value means OI>CO

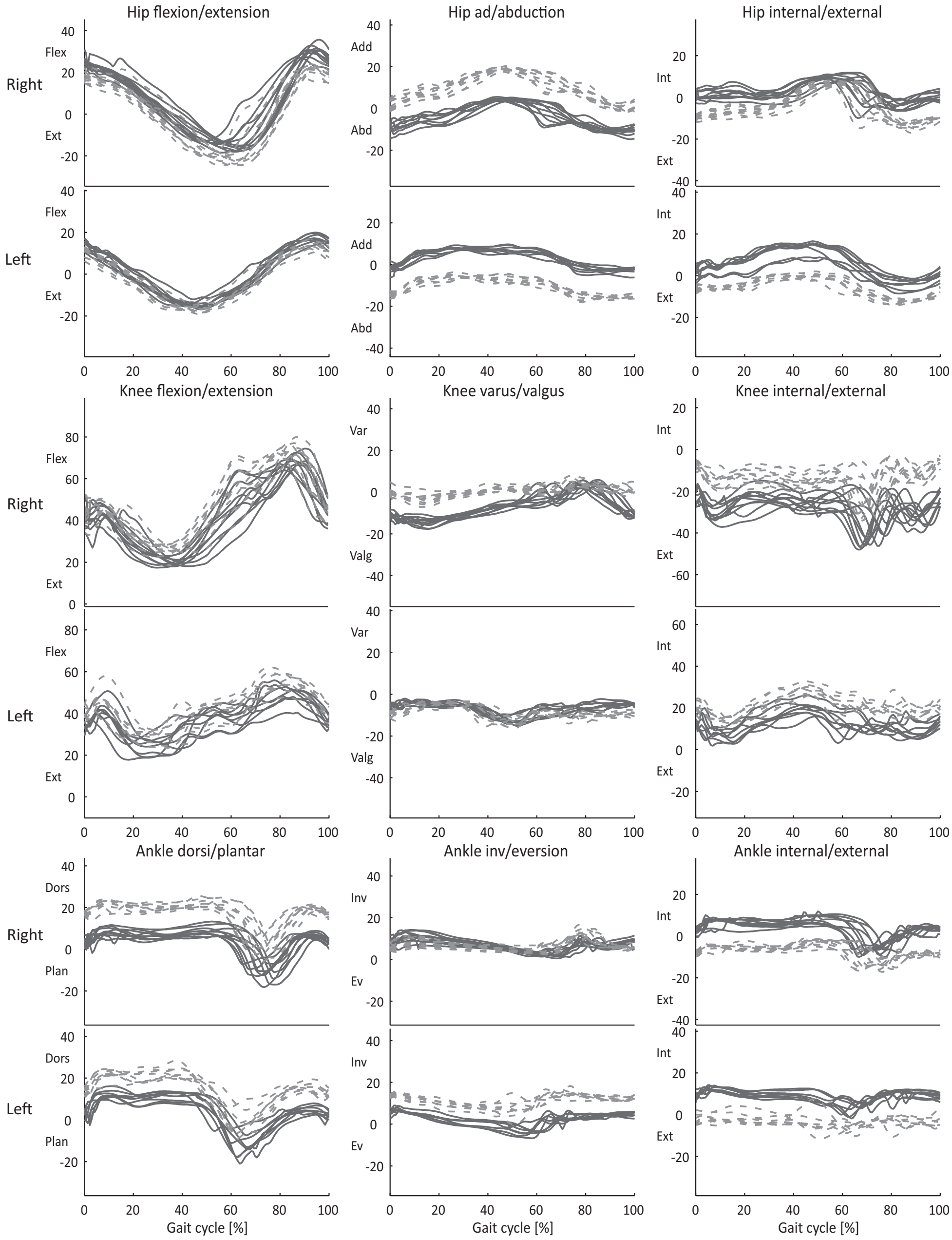


Figure 4.2. Typical example of joint angles of the right and left leg of a child with CP during gait, measured with Outwalk/IMMS (solid lines) and CAST/Optoelectronic (dashed lines). Left colum: sagittal plane; middle column: frontal plane; right column: transverse plane.

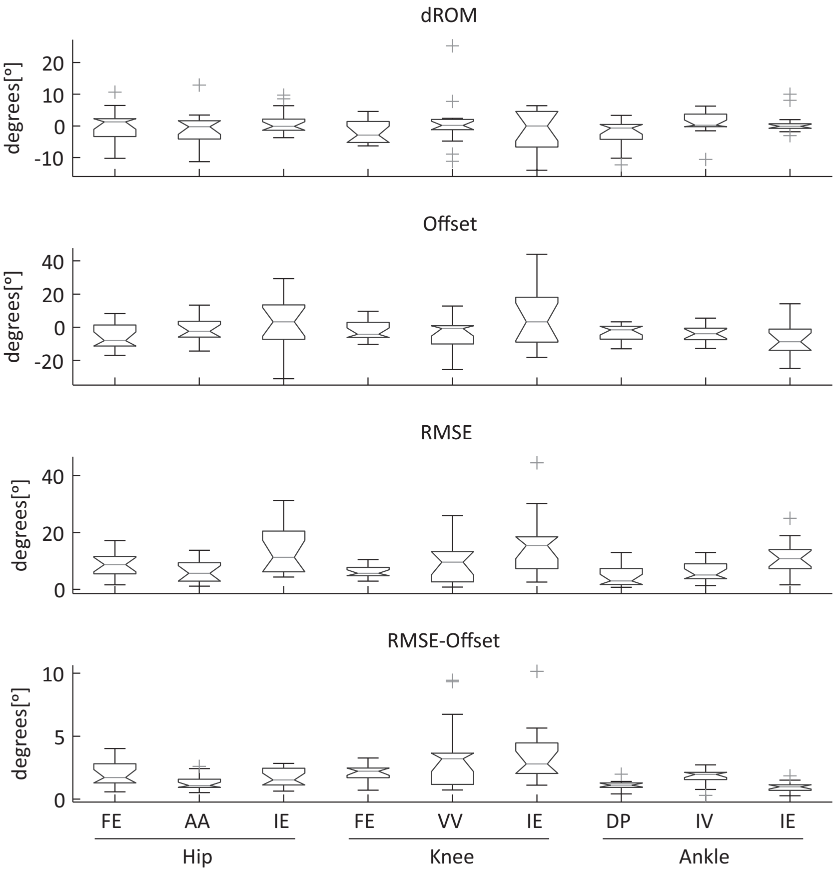


Figure 4.3. Box and whisker plots for Outwalk/IMMS versus CAST/Optoelectronic; the dROM, Offset, RMSE and RMSE-Offset of the hip, knee and ankle joint angles of seven children are shown. FE: flexion/extension, AA: ab/adduction, IE: in/external rotation, VV: varus/valgus, DP: dorsi/plantarflexion, IV: in/eversion

On average, the RMSE values were less than 17^o in the transverse plane (with SDs less than 10^o), and less than 10^o in the sagittal and frontal plane. When the offset was removed, the RMSE values were less than 4^o. This shows that the differences between OI and CO were mainly caused by offsets in the joint kinematics, especially in the transverse plane and in the hip flexion/extension angle. The RMSE values were all higher than the intra-subject variability of the CO (i.e. SD-CO>100%), but after removing the offset, only the ankle and knee frontal plane angles and the knee rotation angle were higher.

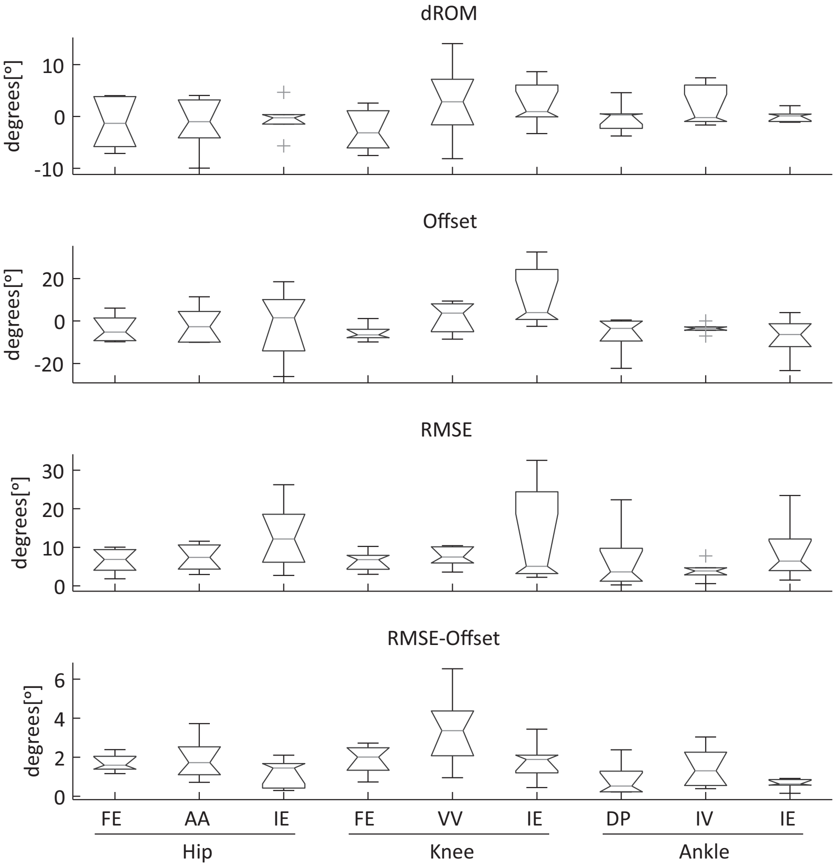


Figure 4.4. Box and whisker plots for Outwalk/Optoelectronic versus CAST/Optoelectronic; the dROM, Offset, RMSE and RMSE-Offset of the hip, knee and ankle joint angles of three children are shown. FE: flexion/extension, AA: ab/adduction, IE: in/external rotation, VV: varus/valgus, DP: dorsi/plantarflexion, IV: in/eversion

Figure 4.4 presents the box and whisker plots of OO kinematics compared to CO kinematics for three children. Similar to the comparison between OI and CO, the most prominent differences were found in the frontal and transverse knee angle, showing that these differences were mainly due to the protocol.

4.5 Discussion

The aim of this study was to validate the application of IMMS, based on the Outwalk protocol, in gait analysis of children with CP. Similar to the kinematics of healthy subjects reported by Ferrari et al. [17], mainly the transverse plane angles were affected by an offset. However, the differences were higher in the children with CP. Apart from the offsets, high maximal differences and RMSE values were observed in the knee frontal and transverse plane angles. After removing the offset (RMSE-offset), the differences in Outwalk/IMMS versus CAST/Optoelectronic were less than 4°, and can therefore not be considered as clinically relevant with respect to the reliability of conventional 3D gait measurements [6].

The offset differences in the transverse plane angles (endo- and exorotation) were also found in the protocol comparison (Outwalk/Optoelectronic versus CAST/Optoelectronic), showing that these differences were due to the protocol (Outwalk versus CAST), and not due to the hardware system (IMMS versus Optoelectronic). In the sagittal hip angle there was also an offset in both the overall (OI/CO) and the protocol (OO/CO) comparison, which indicates that this offset is the consequence of the different biomechanical hip models implemented in the protocols.

The calibration in the Outwalk protocol is based on: functional movement in the knee, static posture (upright or supine), and careful alignment of the pelvis and shank sensor with anatomical structures [11]. In contrast, the CAST protocol uses anatomical landmarks to define the CS of the segment. The differences in the frontal and transverse plane angles of the knee are probably caused by differences in the CS of the thigh. It is well-known that cross-talk is a primary concern for the knee joint [22,23]. Frontal and transverse plane angles are often regarded as unreliable [17,22]. When the knee flexion/extension axis is ill-defined, flexion will be transferred into ab/adduction or internal/external rotation [23]. This may apply to both protocols. For the Outwalk protocol, performance of a pure knee flexion/extension to define the distal thigh CS (the distal CS is the segment CS that is used for the distal joint of the segment [11]) may be more difficult for children with CP than for healthy subjects (particularly in a standing posture), since children with CP have less stability (with increasing GMFCS), bone deformities such as femoral anteversion and tibial torsion, and knee flexion contractures. Although the CAST protocol was used as reference, this protocol may also suffer from inaccuracies, due to the erroneous palpation of bony landmarks [24]. Accurate palpation of bony landmarks, such as the femoral epicondyles, may be more difficult in children with CP when they have bone deformities. Furthermore, soft-tissue artefacts cause a relative movement of skin markers with respect to the underlying bone that may substantially affect knee joint kinematics [25]. It should also be noted that the functional knee axis, defined during a passive, non-weight-bearing, knee flexion/extension movement, does not have to be similar to the axis defined by the femoral epicondyles [26] or to the functional knee axis during gait [27-29].

The distal pelvis and proximal thigh CSs in the Outwalk protocol are defined from the upright static posture, assuming zero flexion, ab/adduction and rotation in the joints. This posture was used, since upright calibration is easier and quicker to perform than a calibration in a supine position, and it has been used in the study of healthy adults [17], that we used for comparison. Obviously, the advantage of upright calibration is a shortage of time needed for the calibration procedure.

However, the upright calibration may have affected the accuracy of the kinematics. Particularly, the offset that was observed in the sagittal hip kinematics of 5 children may have been caused by the use of the upright static posture. In an upright posture the pelvis is normally slightly anteriorly tilted, in the presence of hip flexion [30]. In pathological cases this anterior tilt in upright stance might be even excessive [3]. Moreover, a neutral upright static posture is difficult to maintain for children with irreducible knee flexion, laxity or deformities. Therefore, to correct for pelvis anterior tilt in an upright posture, the hip biomechanical model in the Outwalk protocol should be optimized. This may be achieved by using the actual CS of the sensor on the pelvis, aligned with the posterior superior iliac spines (the proximal pelvis CS [11]), instead of using the assumption that the pelvis is not tilted (the distal pelvis CS, which is currently used for hip kinematics [11]). Furthermore, the Outwalk protocol makes an alternative static trial possible in a supine position, with the hip and knee flexed at a certain known angle to account for flexion and joint deformities [11]. This could optimize the accuracy of the anatomical calibration. However, in unloaded supine posture positions of bones underlying the skin with respect to the sensors attached to the skin might be different from an loaded upright posture. This may influence the accuracy of the anatomical calibration. Moreover, also anatomical calibration in the frontal and transverse plane can be hard to achieve using a static posture in children with CP due to joint deformities or muscle contractures. Therefore, other anatomical calibrations that can be performed in children with CP should be investigated as well.

The KiC algorithm, used for the estimation of the ankle and knee kinematics, does not rely on the use of the IMMS magnetometers [20]. Therefore, these joint kinematics were not affected by a non-homogenous earth magnetic field which may be a main concern in gait laboratories [21]. However, for the hip kinematics, the KiC algorithm was not applied. Therefore, the observed difference in the hip kinematics might also be the result of a non-homogeneous earth magnetic field, caused by the instrumentation (apart from the effect of the upright calibration, as discussed above).

Studies reporting on the reliability of 3D gait measurements with optoelectronic systems have found data errors of less than 5^{o}, with the exception of hip and knee rotations that show larger errors [6]. RMSE values of the OI versus CO were less than 10^{o} in the sagittal and frontal plane, and less than 17^{o} in the transverse plane. When removing the offset, the accuracy of OI was within 4^{o}. These findings show that a laboratory-based reference system and protocol, as well as an ambulatory system and protocol (i.e. OI), are both subject to errors of similar magnitude, mainly in the transverse plane.

To further reduce the offsets of the OI, it is preferable to apply the anatomical calibration in a different static posture (e.g. supine) in children with CP, allowing flexion in the joints, and to adjust the hip biomechanical model. This may further improve the accuracy of IMMS for the measurement of joint kinematics in gait analysis. Furthermore, the inter-rater and intra-rater reliability of the Outwalk protocol should be studied.

4.6 Conclusion

The application of the IMMS is suitable for clinical gait analysis. However, the main differences with the reference system in measuring gait kinematics were found in offsets in ankle and knee rotation and in hip flexion, due to the anatomical calibration. To improve the accuracy of joint kinematic measurements, further studies should focus on the improvement of anatomical calibrations of the IMMS that can be performed in children with CP.

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