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A new anatomically based protocol for gait analysis in children

Alberto Leardini *, Zimi Sawacha, Gabriele Paolini, Stefania Ingrosso, Roberto Nativo, Maria Grazia Benedetti

Movement Analysis Laboratory, Istituti Ortopedici Rizzoli, Via di Barbiano 1/10, 40136 Bologna, Italy

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Abstract

Human movement analysis still suffers from the weakness of the currently used protocols for data collection and reduction. Reliable data comparisons and precise functional assessment require anatomically based definitions of the reference axes and frames, and therefore careful identification and tracking of the landmarks. When impaired children are analysed, the marker-set and other measurement procedures have to be minimised to reduce the time of the experiment and ensure patient collaboration. A new protocol is proposed for the analysis of pelvis and lower limb motion obtained as a compromise between these two requirements.

A marker-set is proposed which involves the attachment of 22 skin markers, the calibration by a pointer of 6 anatomical landmarks, and the identification of the hip joint centre by a prediction approach. Anatomical reference frames and joint rotations are defined according to current recommendations. The protocol was assessed by analysing a single child in several repetitions by different examiners, and a population of 10 healthy children, mean age 9.7-years-old. The entire analysis was repeated after subtraction of the offset by static posture angles. The minimum and maximum means of the standard deviations from five examiners of the same child were respectively 2.1° in pelvic obliquity and 6.8° in knee rotation. The minimum and maximum means of the standard deviations from the 10 healthy children were 2.1° in pelvic obliquity and 9.6° in knee internal–external rotation. The protocol is feasible and allows 3D anatomical-based measurements of segment and joint motion and data sharing according to current standards.

Keywords: Human movement analysis; Anatomical reference frames; Experimental methodology; Marker-set; Kinematic model; Variability; Offset angles

1. Introduction

Following the extraordinary progress that has been made since the developments introduced by the pioneers [1], gait analysis has become a fundamental examination in current clinical practice. The clinical usefulness of gait analysis has been established [2,3], particularly in children with cerebral palsy [4–7].

Reliable intra- and inter-subject comparison of gait patterns and the need to report kinematic variables in clinical terminology require anatomically based definitions of the reference axes and frames. Detailed functional assessment also requires precise identification of deformities of the musculoskeletal system (femur neck anteversion/antetorsion, tibial torsion, foot equinus, etc.). This knowledge is achieved only with a careful identification and tracking of anatomical landmarks, which requires prolonged data collection. The alternative would involve anatomical data based on magnetic resonance imaging of the specific subject [8]. These are rarely available.

On the other hand, procedural distress should be minimized. Children cannot always stand still for a long time, walk wearing a large number of markers, and perform additional motion trials. The marker-set and possible associated anatomical landmark calibration or anthropometric measurement procedures, therefore, must be minimised to contain the time taken for subject preparation and data collection. Finally, positioning the reflective markers should be limited to a few easily accessible locations, particularly in severe musculo-skeletal deformities.

Currently available protocols for motion data collection and reduction have been questioned for their inability to meet adequately these two contrasting requirements. The

* Corresponding author. Tel.: +39 051 6366522; fax: +39 051 6366561.
E-mail address: leardini@ior.it (A. Leardini).

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most commonly used protocol [9–11] involves the acquisition of a very small number of markers and no landmark calibration, but foot motion tracking is not fully 3D, and anatomical planes are defined visually by positioning marker-instrumented wands on the lateral aspect of the thighs and shanks. Wand alignment is also likely to enlarge skin motion artefact effects [12] and variability of the gait results [13]. Moreover, the reliability of some anthropometric measurements seems poor [14]. Another protocol [15] utilises fewer markers, but requires several anthropometric measurements and a special configuration for the cameras. In these two techniques, the complicated definitions render comparisons difficult. The 'anatomical landmark calibration technique' [16–18] enables accurate tracking of a large number of anatomical landmarks, but requires a time-consuming procedure for their identification, and three or more markers for each segment. It has been shown that landmark identification, marker placement, and data reduction affect considerably the calculation of kinematic and kinetic variables [13,19–22].

The purpose of the present work was to design and assess the viability of a novel protocol for the analysis of pelvis and lower limb kinematics able (a) to provide a complete description of 3D segment and joint motion on an anatomical basis, (b) to report these quantities in accordance with the recently proposed international recommendations, and (c) to limit the necessary procedures for data collection and reduction.

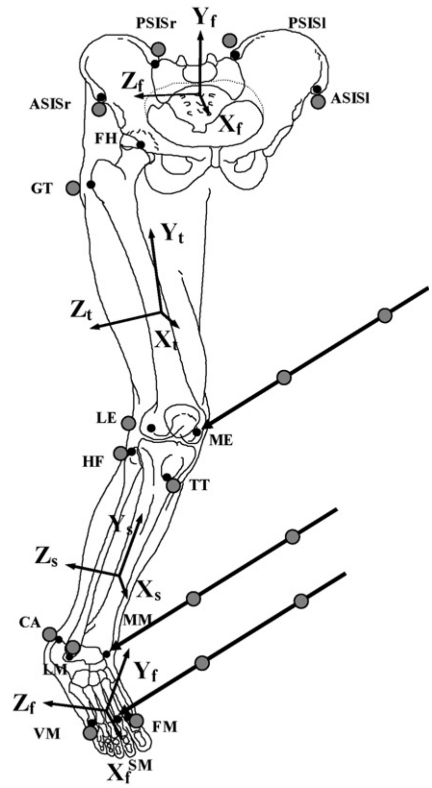

Fig. 1. Diagram showing locations of the anatomical landmarks (small black circles), and the reflective markers (grey circles), including those on the pointer for the three calibrations for each side, and orientation of the anatomical reference frames for the pelvis (p), thigh (t), shank (s) and foot (f) segments.

2. Materials and methods

2.1. Definitions and analytical procedures

The following anatomical landmarks are tracked in space by applying a 10-mm-diameter spherical marker (see Fig. 1) to: the two most anterior and the two most posterior margins of the iliac spines (ASIS, PSIS), the most lateral prominence of the great trochanter (GT) and of the lateral epicondyle (LE), the proximal tip of the head of the fibula (HF), the most anterior border of the tibial tuberosity (TT), the lateral prominence of the lateral malleolus (LM), the aspect of the Achilles tendon insertion on the calcaneous (CA), and the dorsal margins of the first (FM) and fifth (VM) metatarsal heads.

The centre of the femoral head (FH) is assumed to coincide with the centre of the acetabulum, which is reconstructed by a geometrical prediction method based on the location of the four anatomical landmarks of the pelvis [23]. This provides, together with GT and LE, a third point on the femur, which enables reconstruction of a relevant technical frame [24]. The medial epicondyle (ME) is calibrated using a pointer mounting two markers in known positions with respect to the tip [16–18]. Calibrations are performed also for tracking the medial prominence of the medial malleolus (MM), using the three markers on the shank as the relevant technical frame [24], and the dorsal aspect of the second metatarsal head (SM), using the three markers on the foot (assumed as a single rigid segment) as the relevant technical frame. The centres of the hip, knee and ankle joints are taken respectively as the FH, the mid point between LE and ME, and the mid point between LM and MM. The average total time for a single subject preparation and data collection was approximately 30 min.

Anatomical reference frames for the body segments are defined according to previous work [17], which are mostly consistent with relevant international recommendations [25,26]. Standard coordinate systems [27] are adopted for each joint, which entail defining flexion/extension (Flex/Ext) as the relative rotation about axis e_1, taken as the medio-lateral axis (Z) of the proximal segment; internal/external (Int/Ext) rotation (axis e_3) as the relative rotation about the vertical axis (Y) of the distal segment; and abduction/adduction (Abd/Add) as the relative rotation about a 'floating' axis (e_2) orthogonal to these two at each collected sample. This terminology is adopted for the hip and knee joints, but for the special ankle joint these three rotations are referred to respectively as dorsiflexion-plantarflexion (Dors/Plan), inversion/eversion (Inv/Ev), and abduction/adduction. Spatial rotations of the pelvis, respectively tilt, rotation and obliquity, are calculated with the same convention, i.e. at the virtual joint between the laboratory global frame as 'proximal' and the pelvis as 'distal' segments. In addition to the standard 'absolute angle' calculation, subtraction of the 'offset' by the corresponding static posture angle was performed on all joint and pelvic rotations. Joint moments are calculated as the vector product of the position vector of the joint centre and the collected ground reaction force. Internal joint moments are presented, to comply with common practice. The three relevant components are taken as those projected in the joint coordinate system e_1, e_2, e_3.

Table 1
Mean age, height and weight together with mean speed of progression over the 10 children analysed

Test	Sex	Age (years)	Height (cm)	Weight (kg)	Speed of progression (m/s)
Subjects data					
Intra-subject variability	F	9	138	34	1.2 (0.1)
Intra-subject inter-examiner variability	F	7	126	20	1.3 (0.1)
Inter-subjects variability	7 M, 3 F	9.7 (1.2)	137.2 (9.7)	33.4 (9.8)	1.2 (0.1)

2.2. Experimental procedure

Marker trajectories and ground reaction force were collected respectively by an eight-camera motion capture system (Vicon 612, Vicon Motion Systems Ltd., Oxford, UK) and by two force plates (Kistler Instrument AG, Switzerland) at 100 samples per second during barefoot level walking. Ten healthy children were analysed (Table 1) following informed consent. The subjects were asked to walk at their normal speed, and at least 10 trials were analysed.

Three different experiments were performed to assess variability of the measurements at different levels. (1) Intra-subject variability was assessed by analysing 10 walking trials within the same gait analysis session, i.e. a single child with a single marker placement and anatomical calibration. (2) Inter-examiner variability was assessed by analysing three walking trials in another child for five sessions, each performed by a different examiner doing the full procedure of marker placement and anatomical calibration. (3) Inter-subject variability was assessed by analysing 3 walking trials for each of 10 children, with the full procedure performed by a single examiner. The examiners were residents in physical therapy, with 2-year experience in the gait laboratory.

3. Results

(1) Intra-subject variability was very small. Time histories of the mean and standard deviation over the 10 trials of the joint rotations and moments are reported in Figs. 2 and 3, respectively. Corresponding summarising values are reported in Table 2. In particular the average value of the standard deviation throughout the gait cycle (first column) represents variability for each single plot. The most repeatable rotation within the same child was knee Abd/Add (mean S.D. 1.5°) and the least was knee Flex/Ext (5.1°).
(2) Inter-examiner variability was moderately small. Time histories of the mean and standard deviation over the five examiners of the joint rotations and moments are reported in Figs. 4 and 5, respectively. Corresponding summarising values are reported in Table 3. The most repeatable inter-examiner rotations were pelvic obliquity (2.1°) and the least was knee Int/Ext (6.8°).

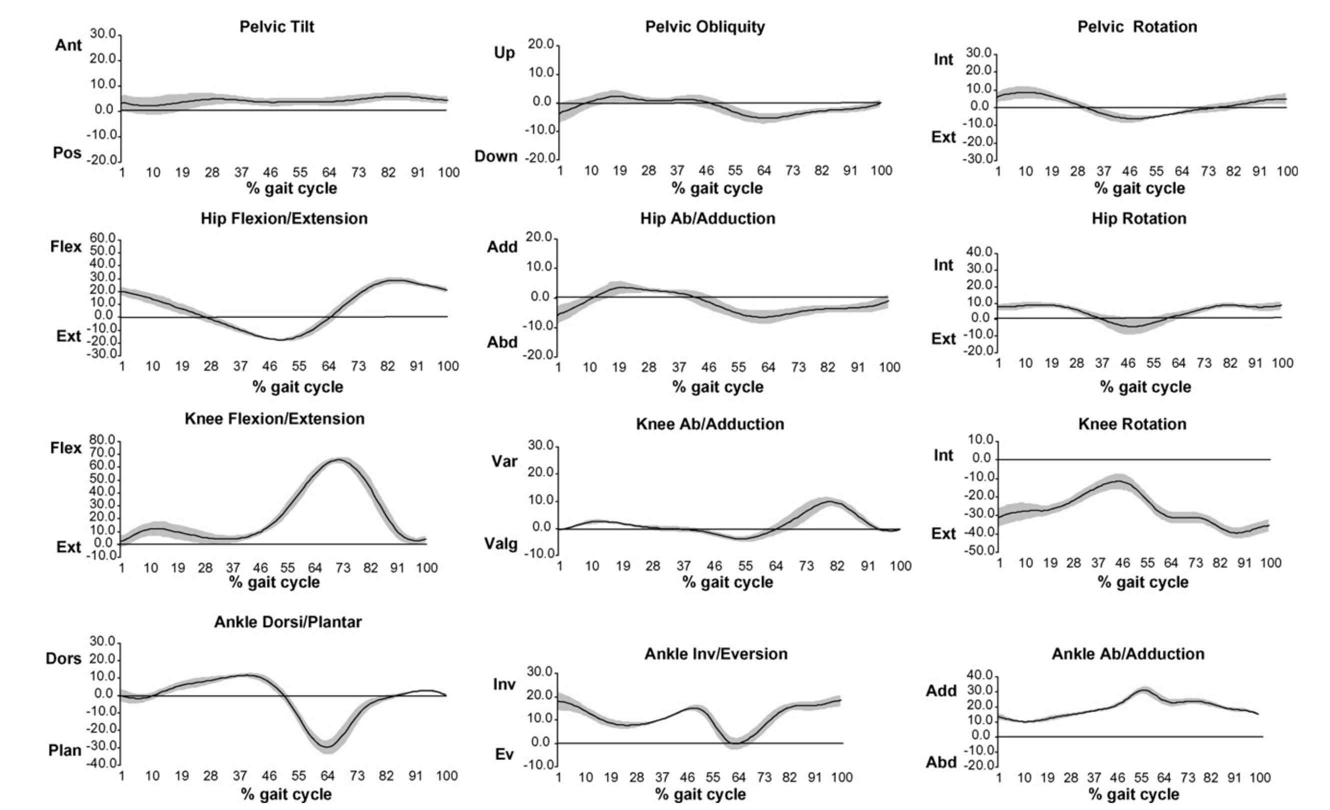

Fig. 2. Joint rotations (absolute angles) about the three axes as mean (solid) plus and minus a standard deviation (grey) over 10 repetitions of the same representative child.

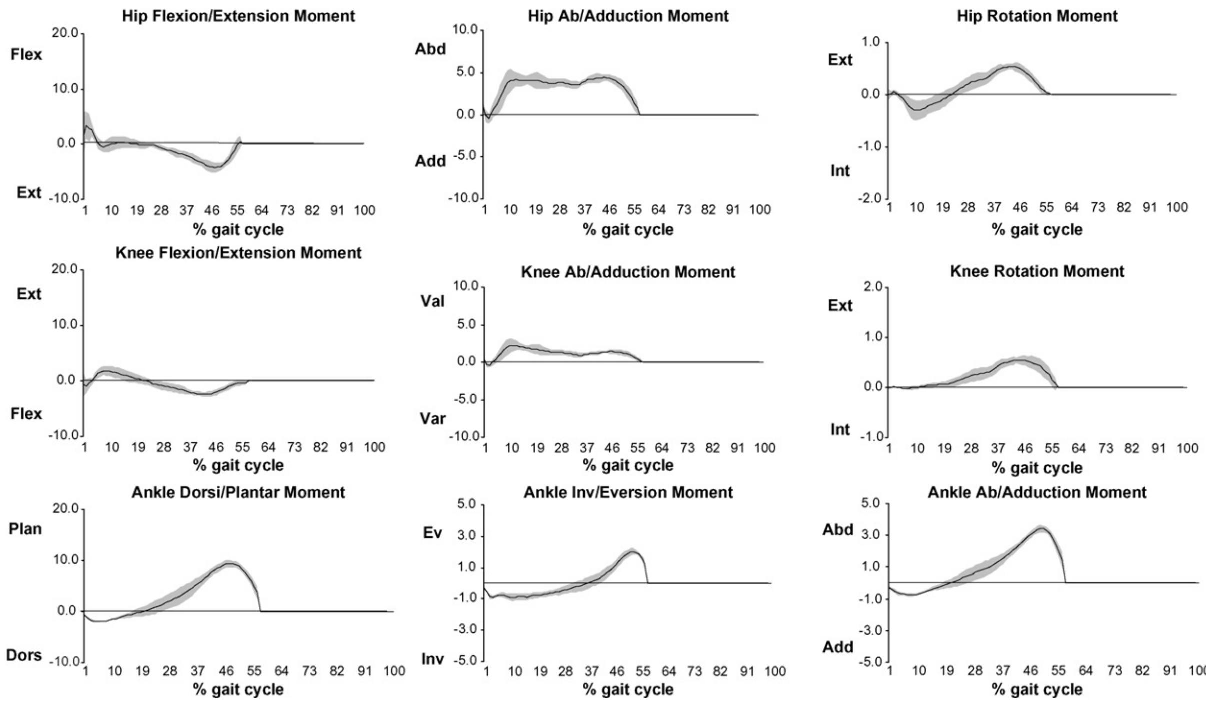

Fig. 3. Joint moments as mean (solid) plus and minus a standard deviation (grey) over 10 repetitions of the same representative child.

(3) Joint rotations and moments calculated from the 10 children (Figs. 6 and 7) were in good agreement with corresponding data obtained with very similar anatomical definitions [18], despite using a very different marker-set in the present study. Corresponding summarising values are reported in Table 4. In this case the most repeatable inter-subject rotation was pelvic obliquity (2.1°) and the least was knee Int/Ext (9.6°).

Table 2
Summarising values of the joint rotations and moments obtained by a single examiner on 10 trials of a single child, both for standard 'absolute angle' and 'offset subtraction' calculations

Rotations (°)	AVG S.D. (all)		AVG M-m (mean trial)		Mean		Max		Min	
	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted
Pelvic tilt	2.3	2.3	7.6	7.6	4.2	−6.3	6.0	−4.4	2.2	−8.3
Pelvic obliquity	1.9	1.9	5.5	5.5	−1.4	−2.0	2.3	1.7	−5.4	−6
Pelvic rotation	2.6	2.6	8.2	8.2	1.0	1.8	8.6	9.4	−6.3	−5.5
Hip flexion/extension	3.5	3.5	10.7	10.7	6.6	4.5	28.7	26.7	−17.5	−19.6
Knee flexion/extension	5.1	5.1	15.3	15.3	22.0	26.9	65.6	70.6	2.4	7.3
Ankle dorsi/plantar	2.9	2.9	9.5	9.5	−1.7	−3.5	11.6	9.7	−29.7	−31.6
Hip Ab/adduction	2.0	2.0	6.3	6.3	−2.0	0.7	3.6	6.2	−6.5	−3.9
Knee Ab/adduction	1.5	1.5	4.7	4.7	1.3	1.1	9.8	9.6	−3.9	−4.2
Ankle Inv/eversion	2.3	2.3	7.1	7.1	11.2	3.3	18.4	10.4	−0.2	−8.1
Hip rotation	2.8	2.8	9.1	9.1	4.7	−5.8	9.0	−1.5	−4.1	−14.6
Knee rotation	3.8	3.8	12.3	12.3	−26.9	−8.5	−11.5	6.9	−39.6	−21.2
Ankle Ab/adduction	2.0	2.0	6.8	6.8	19	5.3	31.2	17.5	10.2	−3.5
Moments (%BWxH)										
Hip flexion/extension	1.0		3.3		−1.0		3.3		−4.2	
Knee flexion/extension	0.8		2.7		−0.5		1.8		−2.4	
Ankle dorsi/plantar	0.9		2.9		2.9		9.4		−1.9	
Hip Ab/adduction	0.8		2.4		3.3		4.4		−0.5	
Knee Ab/adduction	0.5		1.6		1.2		2.2		−0.4	
Ankle Inv/eversion	0.3		0.8		0.0		2.0		−0.9	
Hip rotation	0.1		0.4		0.1		0.5		−0.3	
Knee rotation	0.1		0.3		0.2		0.5		0.0	
Ankle Ab/adduction	0.3		1.0		0.9		3.4		−0.8	

The mean curve over the 10 trials is represented by its mean, maximum and minimum values, in the last three columns. The average value of the standard deviations (AVG S.D.) and of the maximum minus minimum (AVG M-m) over each normalised sample are also reported in the first and second column.

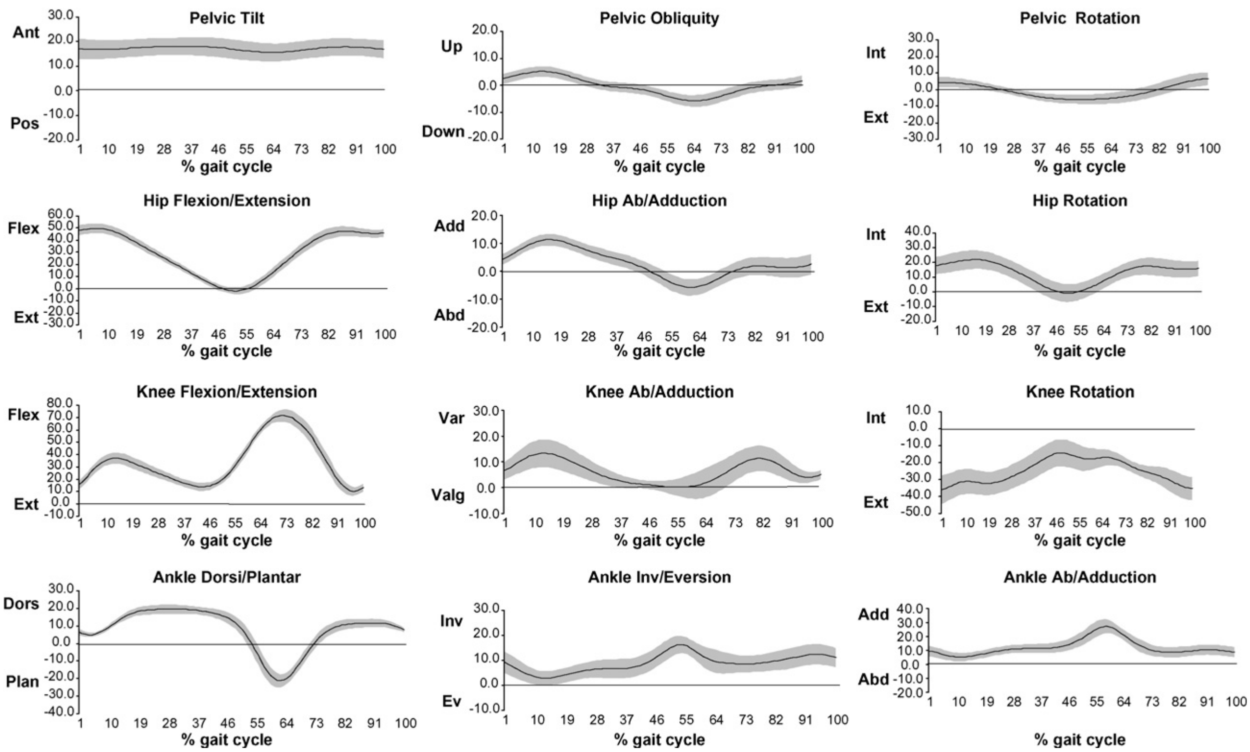

Fig. 4. Joint rotations (absolute angles) about the three axes as mean (solid) plus and minus a standard deviation (grey) over the five examiners on the same child (different from the one reported in Fig. 2).

As expected, average values of the standard deviation throughout the gait cycle were small for the intra-subject variability test, the mean over all the kinematic and kinetic variables being 2.7° and 0.5° %BWxH, respectively (Table 2, first column), a little larger for the inter-examiner test (4.0° and 0.6° %BWxH, Table 3), and the largest for the inter-subject test (5.8° and 1.2° %BWxH, Table 4).

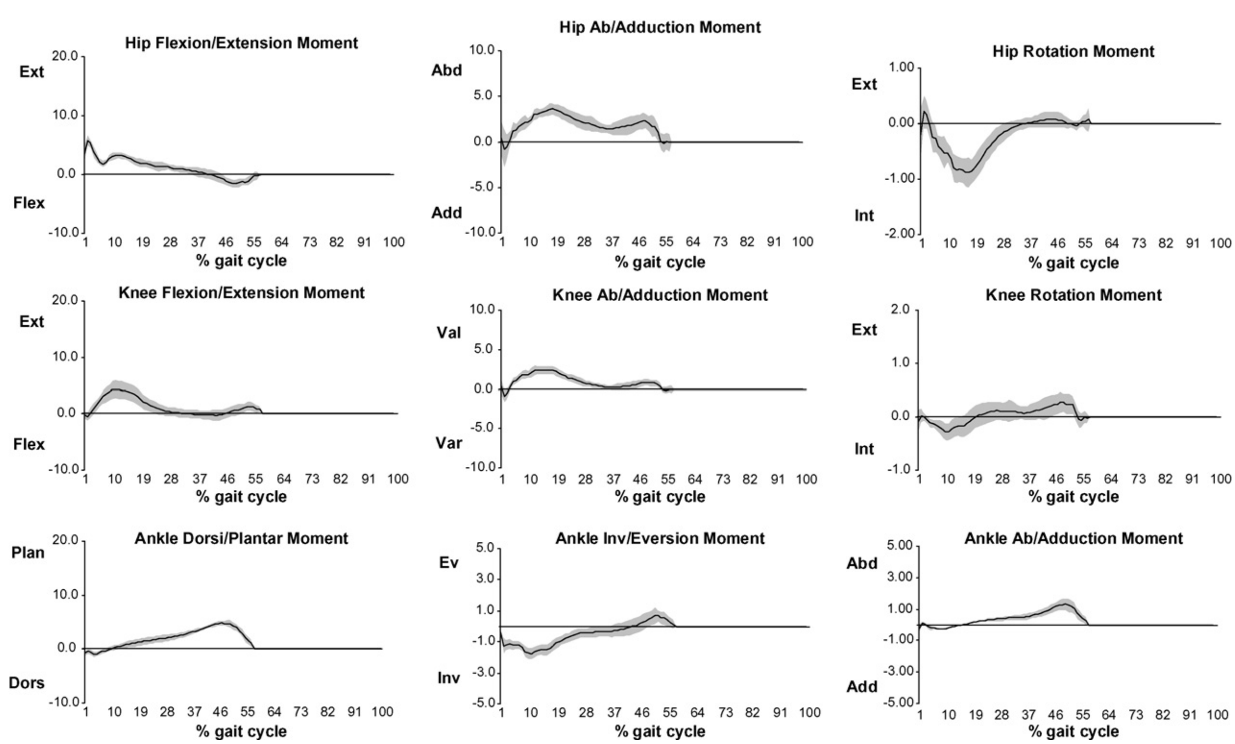

Fig. 5. Joint moments as mean (solid) plus and minus a standard deviation (grey) over the five examiners of the same child (different from the one reported in Fig. 3).

Table 3
Average value of the standard deviation (AVG S.D. 3 × 5 trials) over the walking cycle for joint rotations and moments as measured by five examiners on three repetitions of a single subject, both for standard 'absolute angle' and 'offset subtraction' calculations

Rotations (°)	AVG S.D. (3 × 10 trials)		Mean		Max		Min		AVG S.D. (mean trial)		AVG M-m (mean trial)	
	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted
Pelvic tilt	3.8	2.3	17.1	1.9	18.1	2.8	15.6	0.3	4.0	2.2	9.3	5.3
Pelvic obliquity	2.1	1.4	−0.3	1.0	5.1	6.5	−5.8	−4.6	1.8	0.7	4.5	1.8
Pelvic rotation	3.2	3.1	−0.9	−0.3	6.5	7.1	−6.0	−5.4	2.0	1.8	5.0	4.7
Hip flexion/extension	3.9	5.0	28.7	17.4	49.7	38.4	−1.8	−13.1	3.2	4.6	8.5	11.3
Knee flexion/extension	4.7	4.8	34.0	30.3	71.6	67.9	10.4	6.6	3.1	3.3	7.4	8.0
Ankle dorsi/plantar	3.1	3.1	7.8	−2.4	19.5	9.3	−21.3	−31.7	1.9	2.0	4.7	5.0
Hip Ab/adduction	2.8	2.2	2.7	3.4	11.3	12.0	−5.8	−5.3	2.3	1.4	5.6	3.5
Knee Ab/adduction	4.1	3.9	6.2	5.8	13.3	13.0	0.2	−0.2	4.0	3.7	10.9	9.5
Ankle Inv/eversion	3.9	4.4	8.9	1.8	16.3	9.3	2.9	−4.1	2.3	3.2	5.8	8.2
Hip rotation	6.1	3.3	12.8	6.3	21.9	15.5	−0.9	−7.5	6.3	2.9	16.1	7.4
Knee rotation	6.8	5.0	−25.0	−4.3	−14.2	6.7	−36.0	−15.4	6.8	4.7	16.7	11.6
Ankle Ab/adduction	4.0	2.5	12.2	6.8	27.2	22.0	5.2	−0.3	3.6	1.4	8.4	3.6
Moments (%BWxH)												
Hip Flexion/Extension	0.8		1.2		5.8		−1.6		0.6		1.6	
Knee flexion/extension	1.1		1.3		4.3		−0.5		1.0		2.5	
Ankle dorsi/plantar	0.7		2.0		4.8		−0.9		0.4		1.1	
Hip Ab/adduction	0.9		1.9		3.6		−0.7		0.7		1.7	
Knee Ab/adduction	0.6		0.9		2.4		−0.9		0.4		1.1	
Ankle Inv/eversion	0.4		−0.5		0.7		−1.8		0.3		0.8	
Hip rotation	0.2		−0.2		0.2		−0.9		0.1		0.4	
Knee rotation	0.2		0.0		0.3		−0.3		0.2		0.4	
Ankle Ab/adduction	0.2		0.4		1.3		−0.2		0.1		0.3	

Corresponding mean, maximum and minimum values for the mean curve of these variables are provided in the following three columns (mean, max, min). The same average value of the standard deviation is also measured on the mean curve over the three repetitions for each examiner (AVG S.D. mean trial). Over these mean trials, the average value of the range (max–min) at each sample is also reported (AVG M-m mean trial).

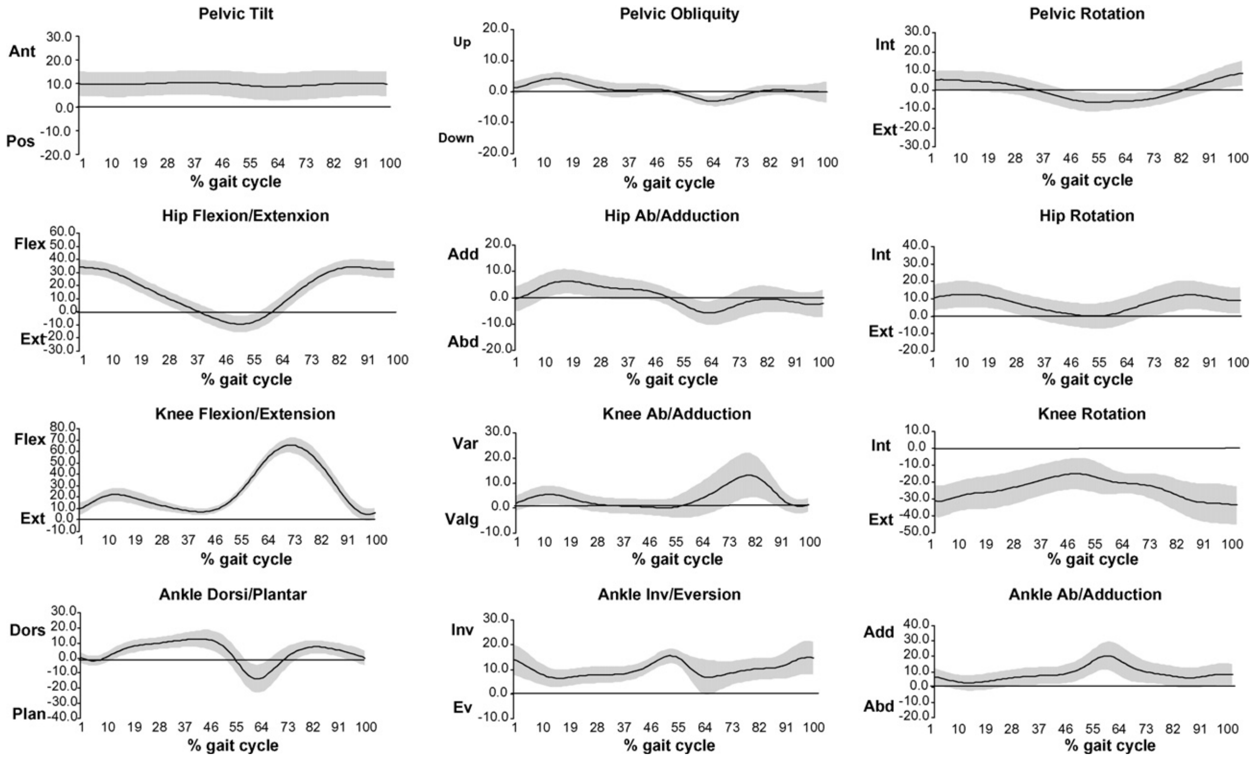

Fig. 6. Joint rotations (absolute angles) about the three axes as mean (solid) plus and minus a standard deviation (grey) over 3 repetitions for all 10 children.

4. Discussion

4.1. Overview

Protocols for clinical gait analysis should pursue a thorough and reliable reconstruction of segment and joint kinematics based on subject-specific anatomical references on one hand, and rapid, simple, and practical procedures of data collection and reduction on the other hand, particularly when children are analysed. Anatomical reference frames should be defined using anatomical landmarks, and these should be chosen to be identified easily, preferably by external palpation, in a repeatable fashion. Minimisation of the effects of experimental errors, such as those associated to skin motion and anatomical landmark identification, as well as being able to report gait results in terms of the current international recommendations are also important criteria for the design of new protocols.

The present proposal was aimed at obtaining a compromise between these contrasting criteria. In particular, external markers were meant to represent internal anatomical landmarks in the largest possible number in order to limit the necessary marker-set. Therefore only six landmark calibrations were necessary. These calibrations can be performed with the conventional pointer [18] or by applying additional markers for a static acquisition only, a procedure that is frequently performed in our routine gait analyses. If necessary, a much larger number of anatomical landmarks can be tracked with the same marker-set just by adding additional calibrations. The marker-set adopted was successfully tracked also in an exemplary test with a five-camera system.

4.2. Advantages

Markers mounted at the ends of lower limb segments (i.e. GT, LE, HF, LM) are expected to be affected less by artefact caused by movement of the large central soft masses [28]. Neither anthropometric measurements nor joint alignment devices are necessary. Knowledge of anatomical landmarks spatial location enables automatic calculation of anthropometric measurements necessary for joint kinetics. Learning and training of the examiners, which is considered to be a critical issue [13], would benefit from the marker-set based on exact anatomical landmark locations which may also reduce intra- and inter-examiner variability. The definitions of the references according to standard recommendations would facilitate the understanding and sharing of gait measurements among laboratories. Finally, motion of the foot is fully 3D and anatomically based.

4.3. Limitations and remaining issues

The markers mounted in the vicinity of joints can be affected by artefacts associated to skin movement [28], although this is common to most of the current protocols. Unlike a previous approach [16–18], the location of the markers is strictly prescribed and not customized according to the specific study or camera arrangement. The restraining effect of the soft tissues by the wrapping bands [12] is lost. Identification of the anatomical landmarks may be less accurate than that achieved by the sharp tip of a pointer [18]. Finally, the proximity of FH and GT makes the estimation of the pose of the femur potentially more affected by tracking errors.

The subtraction of the offset by static posture angles from joint and pelvic rotation time-histories is an option sometimes adopted, aimed at removing the bias associated to anatomical frame definitions. Absolute angles represent well what is directly observed, but bone or joint deformities will result in not comparable motion patterns during walking. On the other hand, rotation after offset removal represents well the dynamic joint motion, but absolute motion is lost. The present study reports plots from the former and tables for both options, though absolute angles are utilised in our individual assessment. After offset subtraction, the inter subject variability (Table 4) was found to be a little reduced in all variables apart from knee Flex/Ext, pelvic obliquity and pelvic rotation.

The most critical remaining issue is the location of the hip joint centre. Most of the current protocols include their own [9–11,15] or associated [29] methods. Although the functional method [16] was reported to perform well [30–32], and other prediction techniques [33] might be more precise, practical and ethical [34] standpoints suggested for the moment the use of the conventional technique by Bell et al. [23].

4.4. Anatomical reference frame definitions

The anatomical frames defined here for the pelvis, femur, and foot have been well established by several previous proposals and recommendations [23,17,26]. The anatomical frame adopted for the femur was among the best performing, in terms of least propagation of the errors associated with the location of the anatomical landmarks, over a large variety of possible definitions, and the single best when only four anatomical landmarks are available [21]. Ankle joint motion is defined differently from a related recommendation [26], which, assumed coincidence of the calcaneus anatomical frame with that of the tibia/fibula in a neutral ankle joint configuration and required knowledge of two additional landmarks on the borders of the tibial condyles. These two landmarks were considered unsuitable for the present protocol, for which a minimum set-up was pursued. Finally, tests on identification of anatomical landmarks [20] revealed that GT had the largest inter- and intra-examiner variability, but in the present proposal this is utilised only for the definition of the technical and not of the anatomical frame of the thigh.

4.5. Inverse dynamics

Joint moments are calculated here by considering the ground reaction force and the joint centre only. A comprehensive calculation would require an inverse dynamics model of the pelvis and lower extremities

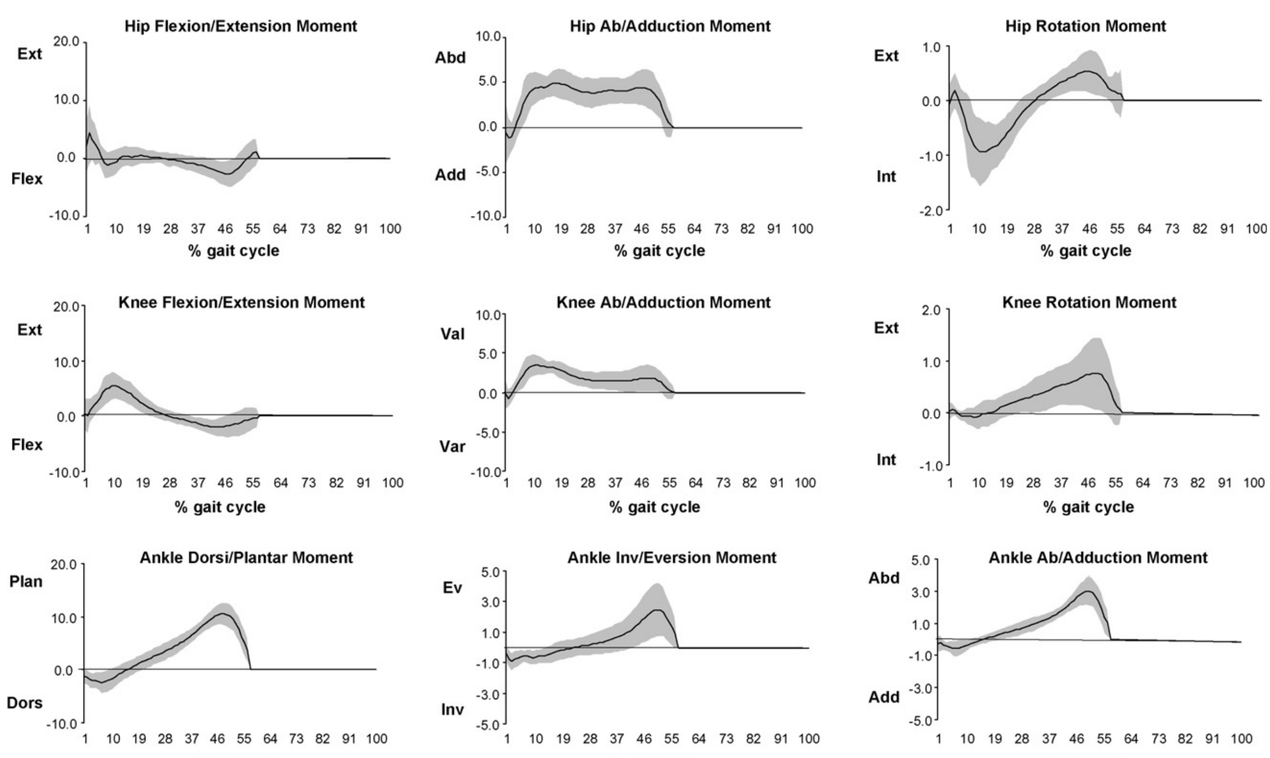

Fig. 7. Joint moments as mean (solid) plus and minus a standard deviation (grey) over 3 repetitions for all 10 children.

Table 4
Average value of the standard deviation (AVG S.D. 3 × 10 trials) over the walking cycle for joint rotations and moments as measured on three repetitions over the control group of 10 subjects by different examiners, both for standard 'absolute angle' and 'offset subtraction' calculations

Rotations (°)	AVG S.D. (3 × 10 trials)		Mean		Max		Min		AVG S.D. (mean trial)		AVG M-m (mean trial)	
	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted	Absolute angle	Offset subtracted
Pelvic tilt	5.6	4.0	9.7	−2.4	10.4	−1.6	8.6	−3.5	5.6	3.8	16.1	12.5
Pelvic obliquity	2.1	2.6	0.5	0.4	4.2	4.1	−3.1	−3.2	1.6	2.3	5.3	7.0
Pelvic rotation	5.2	9.1	0.1	2.3	8.8	11.0	−6.5	−4.3	4.4	8.9	13.4	24.7
Hip flexion/extension	6.5	5.9	16.2	9.5	34.6	28.1	−9.3	−16.0	6.1	5.5	17.5	17.5
Knee flexion/extension	5.8	7.9	25.9	26.3	65.4	65.8	4.9	5.3	4.8	7.3	15.2	24.0
Ankle dorsi/plantar	5.9	4.8	3.7	−0.8	12.8	8.2	−13.8	−18.3	5.5	4.2	17.4	13.6
Hip Ab/adduction	4.7	3.6	0.5	0.7	6.3	6.4	−5.7	−5.6	4.4	3.2	13.9	9.6
Knee Ab/adduction	4.9	4.2	4.0	4.1	13.1	13.2	0.1	0.2	4.8	4.1	15.4	12.3
Ankle Inv/eversion	4.7	4.1	10.0	2.3	15.5	7.7	6.4	−1.3	4.2	3.5	12.6	10.6
Hip rotation	7.6	6.2	7.5	3.2	12.6	8.3	0.1	−4.2	7.7	6.2	25.4	22.6
Knee rotation	9.6	8.1	−24.2	−6.0	−15.0	3.2	−33.6	−15.4	9.6	8.0	32.8	27.0
Ankle Ab/adduction	7.0	4.4	8.5	4.2	20.3	16.0	2.7	−1.6	6.9	4.0	21.8	12.2
Moments (%BWxH)												
Hip flexion/extension	2.0		−0.3		4.4		−2.6		1.8		5.5	
Knee flexion/extension	1.9		0.7		5.5		−2.0		1.5		4.7	
Ankle dorsi/plantar	1.8		3.7		10.5		−2.4		1.6		5.0	
Hip Ab/adduction	1.8		3.5		4.9		−1.2		1.7		5.4	
Knee Ab/adduction	1.3		1.8		3.5		−0.7		1.2		3.9	
Ankle Inv/eversion	0.9		0.4		2.5		−0.9		0.9		2.8	
Hip rotation	0.4		−0.1		0.5		−0.9		0.3		0.9	
Knee rotation	0.4		0.3		0.8		−0.1		0.3		1.1	
Ankle Ab/adduction	0.5		0.9		3.0		−0.6		0.4		1.4	

Corresponding mean, maximum and minimum values for the mean curve of these variables are provided in the following three columns (mean, max, min). The same average value of the standard deviation is also measured on the mean curve over the three repetitions for each subject (AVG S.D. mean trial). On these mean trials, the average value of the range (max–min) at each sample is also reported (AVG M-m mean trial).

represented as a kinematics chain of rigid segments and Newtonian mechanics equations. However, it has been shown that mass-inertial properties are small at the ankle and the knee and that at the hip the gravitational and inertial components are approximately equal and opposite [35]. Reliability of final estimations is influenced by the number of these segments and their associated inertial parameters. It has been shown [36] that in current such models the calculated residual moments at the trunk can be far from the ideal zero, and that the role of the number of segments far exceeds that of the inertial parameters. This concurs with the observation that the inertial contribution in the motor tasks typically analysed is negligible [37]. Finally, the joint moment curves were in good agreement with those of the literature [18,38,39].

4.6. Comparison of the results

Comparison of joint rotation and moment patterns with those of the literature should start from the consideration that the mean age of the 10 children was 9.7 years, and that for the intra-subject variability test was 7 years. Published reports for this age frame are rare [40,41], and the most important relevant data set [42,43] is on children younger than 7-years-old. After this age, the gait is usually considered to be mature.

The general pattern and the range of rotations of the pelvis in the three planes are all in good agreement with the literature when exploring inter-subject repeatability [1,38–44]. When looking at the single subjects (intra-subject and inter-examiner repeatability), a different behaviour is evident between the two children and among the whole sample, as presumed by the above consideration on the repeatability of gait patterns at this age. It was claimed recently [45] that the tracking of markers mounted over a rigid plate attached to a palpable bony area of the pelvis is not different from that based on original marker-sets with single landmarks over bony prominences. Our experience, based previously on markers mounted over a rigid plate wrapped around the anterior iliac crest [18], and currently on the present study, seems to indicate that single skin markers are more capable of identifying subtle pelvic rotations, although real skeletal motion is not known.

The knee and ankle joint rotations are also well consistent with those reported in the literature. These are known to be affected [22,24] by cross-talk, particularly Abd/Add and Int/Ext. The larger bands for these rotations at the knee represent the effect of landmark calibrations performed by the different examiners, both within the same child (Fig. 4) and among children (Fig. 6). Whereas knee Abd/Add is likely to suffer from the cross-talk of knee Flex/Ext (Figs. 2, 4 and 6), Int/Ext may combine this with the effect of the likely antero-posterior motion of the LE and GT landmarks. Although patterns of knee Int/Ext are somehow consistent, intra-subjects (Figs. 2 and 4) and a general trend can be appreciated (Fig. 6); these definitely exaggerate the small physiological motion at this joint. Overall, the knee joint is known to be the most affected by skin motion artefact, and careful analysis of its Abd/Add and Int/Ext is recommended. In addition, variability among motion analysis laboratories utilising the same protocol [13], has highlighted that the lowest variability was for joint motion not requiring alignment of wands and joint centre calculation. This suggests that variability is predominantly due to differences in marker placement by clinicians. Comparison of the present results for the ankle Int/Ext is difficult because of the unavailability of corresponding reports in the literature. The slight abduction and adduction respectively during the first and second double support phases are however consistent with physiological and clinical knowledge.

4.7. Figures of variability

Definition of variability in kinematic and dynamic measurements in gait analysis has not been established. After early attempts to find a single figure to describe variability, the recent trend [13] is for a simple reporting of the average standard deviation throughout the gait cycle. Both the coefficient of multiple correlation [38] and the coefficient of variation [45] seem inappropriate. This is firstly because the values calculated depend on the mean value of the variable to be described, and secondly because the units are difficult to be interpreted clinically. Particularly for the former, high values of variability can result from a low mean value of the variable of interest rather than a high average standard deviation. Three series of plots and tables were provided to show distinct and non-biased figures of the various sources of variability, i.e. the genuine variability of walking patters within and among subjects and the variability introduced by the examiners. The variability of the measurements obtained by the proposed protocol was small, and increased when moving from experiment 1 to 3. The sources of variability associated with measurement errors are discussed above and elsewhere [28,46]. The accepted conclusion was that soft tissue related error was far greater than instrumental or modelling error. Finally, when the mean absolute variability was calculated, most of the present study values compare very well with those corresponding from the literature (Table 5). However, comparison is arduous because of the much younger age of our subjects, the pathological conditions of the other studies' subjects, the present off-set based data reduction, and the possible additional variability introduced by using different lab settings.

4.8. Future developments

In the future, more robust validation of the repeatability of these measurements can be performed. The kinematics of the trunk, which is crucial for the interpretation of lower limb joint moments, also deserves special attention. The dorsal aspect of the second metatarsal head (SM) can be identified alternatively as a fixed proportional distance from

Table 5
Comparison table for the 'mean absolute variability' [48] of a few kinematics variables, the last two being from the present study, the first three columns from the literature

	Paper [13]	Paper [47]	Paper [48]	Present study, 'absolute angle'	Present study, 'offset subtraction'
Pelvic tilt	14.8	13.9	10	9.3	5.3
Pelvic obliquity	6.0	3.6	5	4.5	1.8
pelvic rotation	5.9	6.2	10	5.0	4.7
Hip Flex/Ext	17.1	17.1	14	8.5	11.3
Hip Int/Ext	28.3	33.8	27	16.1	7.4
Knee Flex/Ext	17.3	9.3	13	7.4	8.0
Ankle Dors/Plan	12.1	6.1	12	4.7	5.0
Ankle Inv/Ev			23	5.8	8.2

These latter were obtained from a single subject among 24 examiners and 12 sites, before [13] and after [47] a training program, and from 11 subjects among 4 sites [48]. These are compared with the corresponding obtained in the present study: from a single subject among five examiners over the mean of three repetitions (those obtained in experiment 2: inter-examiner variability, reported in Table 3), both as absolute angles and after offset subtraction. Values are all in degrees.

FM over the vector FM–VM, thus saving the two relevant calibrations. This mean proportional distance over the 10 healthy children analysed was found to be 39.5% (S.D. 4.3). Several critical issues are still open, such as repeatable identification of anatomical landmarks and skin motion artefact effects, which certainly leave, for example, rotations of the knee out of the sagittal plane still unrealistic [3,17,28]. Techniques based on weighted least square optimisation can still be applied for improving bone pose estimation.

4.9. Concluding remarks

Although original technical limitations in clinical gait analysis have been resolved by improvements in modern instrumentation, limitations are still present in the current data collection and reduction protocols. A newly developed protocol is proposed here, to suggest a potential solution to many of the current issues. This is particularly suitable for children, but it can also be used in adults. The markers necessary for the analysis can be mounted quickly, cause little distress to the subject, and are all tracked easily with five- to eight- camera stereophotogrammetric systems. It appears to be also appealing to clinicians because of the familiarity of the skeletal model and marker-set. As the protocol is based on the identification of anatomical landmarks only, examiner training would only include instructions for landmark palpation (see for example [49]). Three-dimensional anatomically based segment and joint motion descriptors, including the foot, are adopted in accordance with recent recommendations. The present preliminary application in a population of healthy children supports its viable implementation in routine clinical gait analysis to a wide range of patient populations.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2006.12.018.

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