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Gait & Posture 28 (2008) 207–216
www.elsevier.com/locate/gaitpost

Quantitative comparison of five current protocols in gait analysis

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Received 23 May 2007; received in revised form 29 September 2007; accepted 27 November 2007

Abstract

Data collection and reduction procedures, coherently structured in protocols, are necessary in gait analysis to make kinematic and kinetic measurements clinically comprehensible. The current protocols differ considerably for the marker-set and for the biomechanical model implemented. Nevertheless, conventional gait variables are compared without full awareness of these differences.

A comparison was made of five worldwide representative protocols by analysing kinematics and kinetics of the trunk, pelvis and lower limbs exactly over the same gait cycles. A single comprehensive arrangement of markers was defined by merging the corresponding five marker-sets. This resulted in 60 markers to be positioned either on the skin or on wands, and in 16 anatomical landmark calibrations to be performed with an instrumented pointer. Two healthy subjects and one patient who had a special two degrees of freedom knee prosthesis implanted were analysed. Data from up-right posture and at least three gait repetitions were collected. Five corresponding experts participated in the data collection and analysed independently the data according to their own procedures.

All five protocols showed good intra-protocol repeatability. Joint flexion/extension showed good correlations and a small bias among protocols. Out-of-sagittal plane rotations revealed worse correlations, and in particular knee abduction/adduction had opposite trends. Joint moments compared well, despite the very different methods implemented. The abduction/adduction at the prosthetic knee, which was fully restrained, revealed an erroneous rotation as large as 30° in one protocol. Higher correlations were observed between the protocols with similar biomechanical models, whereas little influence seems to be ascribed to the marker-set.

Keywords: Gait analysis; Inter-protocol repeatability; Kinematics; Kinetics; Data reduction

1. Introduction

Protocols of gait analysis are intended to make kinematics and kinetics of pelvis and lower limbs clinically interpretable [1–4]. A protocol defines a biomechanical model and the procedures for data collection, processing, analysis and reporting of the results. Historically, probably because of the constraints implied in the pioneering technology, only few laboratories have developed their own protocol independently according to specific clinical requirements [5]. In addition to the different marker-sets and collection procedures, many important differences exist between the current protocols also in the biomechanical model, which includes the measured variables, degrees of freedom assigned to the joints, anatomical and technical references, joint rotation conventions and terminology. In spite of these differences, gait analysis data are shared, exchanged and interpreted irrespectively of the protocol adopted. Recent international initiatives in clinical gait analysis, such as web-accessible services for data repository

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doi:10.1016/j.gaitpost.2007.11.009

[6] or data processing [7], do not impose strict rules about the explicit indications of the protocol adopted. Although the considerable methodological differences are expected to produce inconsistent results, and therefore affect considerably the clinical interpretation, it is still unknown to what extent the different protocols used worldwide compare to each other.

The original 'Newington model' [8,9] is the pioneer and the most commonly used technique for gait data acquisition and reduction. It has been also the basis of many commercial software packages, the most recent being Plug-in Gait (PiG—Vicon Motion Systems, Oxford, UK). The protocol developed at the 'Servizio di Analisi della Funzione Locomotoria' (SAFLo- [10]) implemented different segmental anatomical references and external marker configurations. A little later, a distinction between internal anatomical landmarks and external technical markers was introduced [11]. This 'Calibration Anatomical System Technique' (CAST) was followed by definitions of the references [12] and a standard application [13]. Taking advantage of recently published recommendations [14,15], the protocols 'Laboratorio per l'Analisi del Movimento nel Bambino' (LAMB) [16] and 'Istituti Ortopedici Rizzoli Gait' [17] were also proposed. The latter was the basis of the software 'Total 3D Gait' (T3Dg—Aurion s.r.l., Milan, Italy).

The precision and accuracy of gait analysis experiments are certainly influenced by the instrumentation used [18] but particularly by the interposition of soft tissues between markers and bones, which have unpredictable effects [19,20]. In addition, there is natural intra-subject variability [21,22], particularly associated to different walking speeds. Furthermore, large differences have been observed among subjects [23–27], mainly associated to age, gender, body mass index and probably to ethnic characteristics. Intra- [28] and inter-examiner [29] gait data variability, resulting from inconsistent bony landmark identification and marker positioning, has also been underlined. Inter-laboratory variability has also been analysed, before [5] and after [30] relevant instructions provided to the examiners. However, all of these studies were based on the 'Newington model' or its modifications, limiting the figures of variability to that single protocol. A quantification of inter-protocol variability is fundamental to separate the variability associated to the protocol in itself from that of all the other sources. Only a partial comparison between two software versions of the 'Newington model' has been reported [31]. Considerable differences were revealed in many variable peaks although the mean difference over the gait cycle was less than 1°.

The purpose of the present study was to assess the inter-protocol variability of five different protocols and this was achieved by analysing exactly the same gait acquisition. In order to remove the variability associated to repeated gait cycles and to focus on variability associated to more conceptual differences, a single comprehensive marker-set was devised from the union of the corresponding five. This would contribute to giving a quantitative picture of all the sources of variability, from the intra-subject to the inter-protocol. By looking at several repetitions of the gait cycle, we were aimed also at comparing intra- with inter-protocol variability. Finally, the performance of these protocols was compared also by analysing the errors implied in a special condition where one joint degree of freedom was known a priori.

2. Materials and methods

A single marker-set was designed to implement the five protocols under analysis, i.e. T3Dg [17], PiG [8,9], SAFLo [10], CAST [13], LAMB [16], by limiting the total number of necessary markers. This ultimately included 60 markers (Fig. 1): 22 on each leg, 5 on the pelvis and 11 on the trunk. The lateral and medial epicondyle markers were included in a special cluster of three markers clamped to the femoral condyles as required by SAFLo [10]. The two medial malleoli markers were removed after static up-right posture acquisition. As for the CAST, four technical markers were attached to each segment [13,19,32]. The great trochanter, medial and lateral epicondyles, medial and lateral malleoli, head of the fibula and tibial tuberosity were also calibrated in each leg by using a pointer on which two markers were located at known distances from the tip [11–13]. All the other landmarks necessary for this protocol were calibrated by using corresponding markers in a single static up-right posture.

Two asymptomatic subjects (AF: 24 years, 188 cm, 74 kg; BM: 24 years, 181 cm, 89 kg) and one patient (SZM: 54 years, 177 cm, 95 kg) were analysed. The latter had a special knee prosthesis (MRH Knee, Stryker Corporation) implanted, which allows rotations about the medio-lateral axis of the femur (flexion/extension) and about the longitudinal axis of the tibia (internal/external rotation), while preventing fully abduction/adduction.

Marker trajectories and ground reaction forces were collected, respectively by an eight-camera motion capture system (Vicon 612, Vicon Motion Systems Ltd., Oxford, UK) and two force plates (Kistler Instrument AG, Switzerland) at 100 samples per second. Data acquisitions were carried out in the presence of experts for each protocol, who performed all together landmark identification and marker mounting. Each expert took the relevant anthropometric measures required by his own protocol independently. The subjects were asked to walk barefoot at their natural speed, and five to six walking trials were recorded.

After each acquisition session, 3D marker trajectories were reconstructed and the right and left stride phases were identified. At least three gait cycles for each limb were selected on the basis of good quality of the marker trajectories and ground reaction forces. For each selected gait cycle, the marker trajectories of each marker-set were extracted from the data file and provided to the expert of each protocol together with relevant ground reaction forces. Distinct procedures for data filtering or smoothing, those characteristic of each protocol, were applied independently by each expert. Neither normalisation nor off-set subtraction was performed. Relevant gait analysis results from the five elaborations and from the repetitions were then superimposed in relevant plots, with a careful comprehension of the variable correspondences, regardless of the different terminology adopted. The variable units were unified, i.e. segment and joint rotations were expressed in degrees and joint moments in Newton metre (N*m).

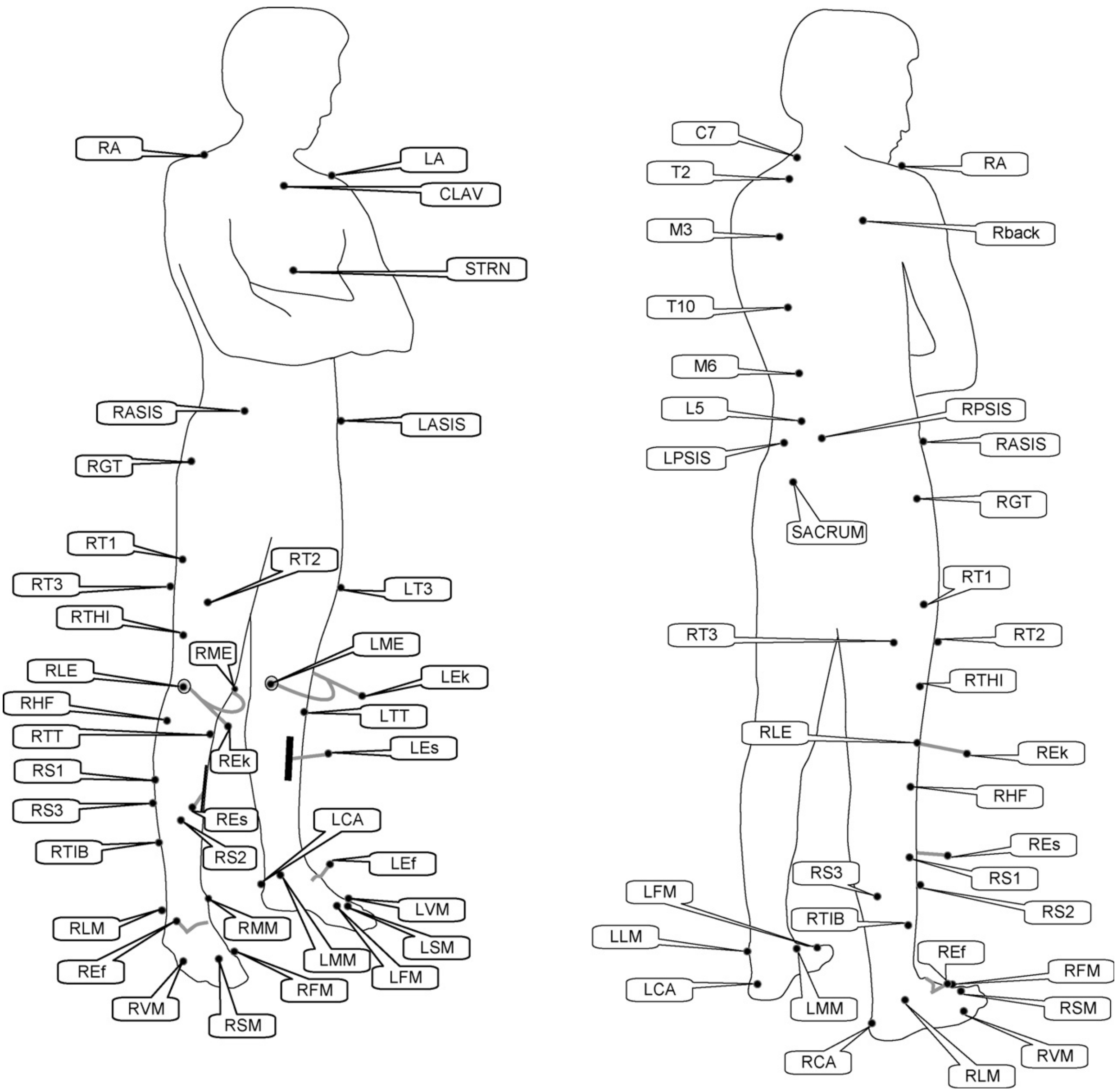

Fig. 1. Diagram of the marker-set (antero-lateral—left and postero-lateral—right views) implemented for the experiments.

The mean absolute variability (MAV), i.e. maximum minus minimum values along each frame averaged over all samples of the gait cycle [5,17,29,30], was calculated for each variable. Once normalised by the range of the variable, the mean relative variability (MRV%) was obtained. As for the joint moments, MAV and MRV% applied only to the stance phase because CAST and T3Dg assume a zero value in the swing phase. In order to identify separately intra-subject variability, MAV and MRV% were also calculated for some variables that are independent from protocol-based processing, i.e. the vertical co-ordinate of markers and ground reaction force. Coefficients of correlation (Pearson moment) between any possible couple of protocols were calculated by standard statistical analysis (Matlab, Mathworks, USA), as used elsewhere [33]. The significance level of each correlation coefficient was obtained by computing the *p*-value. If the *p*-value was small, say less than 0.001, the correlation was statistically significant. The mean over trials of the correlation coefficients for each gait variable was calculated after a 'z-distribution' transformation [34].

3. Results

A very small intra-subject variability for both kinematic and kinetic results was observed in each subject. In subject AF, MRV% for the vertical co-ordinate of the sacrum, lateral epicondyle and lateral malleolus was 9.0%, 9.2% and 4.9%, respectively. MRV% of the vertical, medio-lateral and antero-posterior components of the ground reaction force was 4.7%, 11.3% and 5.6%, respectively. For these six variables, the corresponding coefficients of correlations

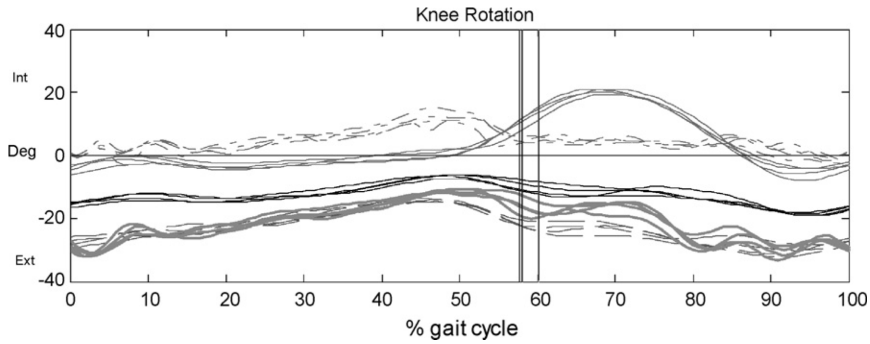

Fig. 2. Internal/external rotation at the left knee of subject AF as calculated by T3Dg (dash), PiG (dot lines), SAFLo (dash-dot), CAST (black solid), and LAMB (grey thick-solid) for all four trial repetitions.

were 0.979, 0.979, 0.995, 0.973, 0.992 and 0.992, all with $p < 0.001$. Because the variability over repetitions is much smaller than that over protocols (Fig. 2), a single representative trial is reported from now on.

Intra-protocol repeatability was high and similar for each protocol (Table 1). Not a single protocol was found particularly sensible to subject variation over repetitions. In particular, MAV was confined to 5° for the pelvis rotations, 7° for all joint rotations and 18 N*m for joint moments.

Overall, a general uniformity was found among the five protocols for most of the variables in all three subjects, a typical subject – AF – being reported in Figs. 3 and 4. Good consistency was observed for all joint flexion/extensions, acceptable consistency was found for pelvic rotations, for hip out-of-sagittal plane rotations and for all joint moments. Poor consistency was found for trunk rotations and out-of-sagittal plane rotations in knee and ankle joints. In particular, though limited to the swing phase, abduction/adduction of the right knee (Fig. 3) reveals large adductions in PiG, small adductions in T3Dg and LAMB, nearly no motion in SAFLo, and small abductions in CAST.

Correspondingly, inter-protocol variability was obtained (Table 2), confining MAV to 21 N*m for the joint moments, but with peaks of 31° and 27°, respectively for knee internal/external rotation and ankle dorsi/plantarflexion. This was obtained with a full analysis of the trials for each variable, i.e. by joining the four repetitions in a single virtual trial composed of the sequential series of the four performed by subject AF. For a few variables, the results from the right and

Table 1
Intra-protocol variability along the four trials across each joint rotation and moment variables for subject AF

Protocols	T3Dg		PiG		SAFLo		CAST		LAMB	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Rotations (°)										
Pelvic tilt	1.4		1.5		1.8		1.4		1.4	
Pelvic obliquity	1.0		1.0		1.0		0.9		1.0	
Pelvic rotation	4.8		4.8		4.8		4.9		4.1	
Hip flexion/extension	3.3	2.8	3.5	3.0	3.2	3.8	3.4	2.6	3.5	2.9
Hip abduction/adduction	1.7	2.5	1.9	2.7	2.3	2.4	1.7	2.6	1.9	2.7
Hip internal/external rotation	3.1	2.9	3.8	2.9	4.6	6.3	3.5	3.0	4.1	2.9
Knee flexion/extension	3.5	2.0	3.4	2.2	3.1	3.1	3.4	2.1	3.5	2.1
Knee abduction/adduction	1.3	1.2	1.5	1.3	1.8	1.6	1.0	0.8	1.0	1.0
Knee internal/external rotation	2.7	2.7	2.7	2.4	4.0	2.9	1.9	2.1	3.4	3.1
Ankle dorsi/plantarflexion	2.4	2.3	2.5	2.1	2.1	2.4	2.1	2.1	2.7	2.4
Ankle eversion/inversion	1.6	1.8			1.2	2.3	1.6	1.7	0.5	0.8
Ankle abduction/adduction	2.5	3.4			2.0	3.1	1.5	3.1	0.6	0.8
Moments [N*m]										
Hip flexion/extension	12.5	17.4	14.0	15.5	13.0	15.6	12.8	17.1	10.1	15.6
Hip abduction/adduction	7.9	10.0	7.3	7.9	8.0	9.6	8.2	10.2	5.5	7.3
Hip internal/external	2.0	1.1	2.2	2.0			2.1	1.4	1.7	1.0
Knee flexion/extension	8.7	11.9	8.3	11.5	8.0	9.7	9.2	11.6	9.9	11.9
Knee abduction/adduction	4.0	6.8	3.6	5.7	3.7	6.1	4.4	6.4	3.6	5.7
Knee internal/external	1.5	0.9	2.6	1.8			1.6	1.1	1.5	1.1
Ankle dorsi/plantarflexion	14.0	9.2	14.7	9.6	14.3	11.5	13.9	9.7	16.0	11.0
Ankle eversion/inversion	3.8	4.3			2.4	5.9	3.9	4.2	3.0	2.9
Ankle abduction/adduction	4.1	3.2					1.4	1.6	5.3	4.0

The average value of the maximum minus minimum over each sample (MAV) is reported for the right and left leg for each protocol.

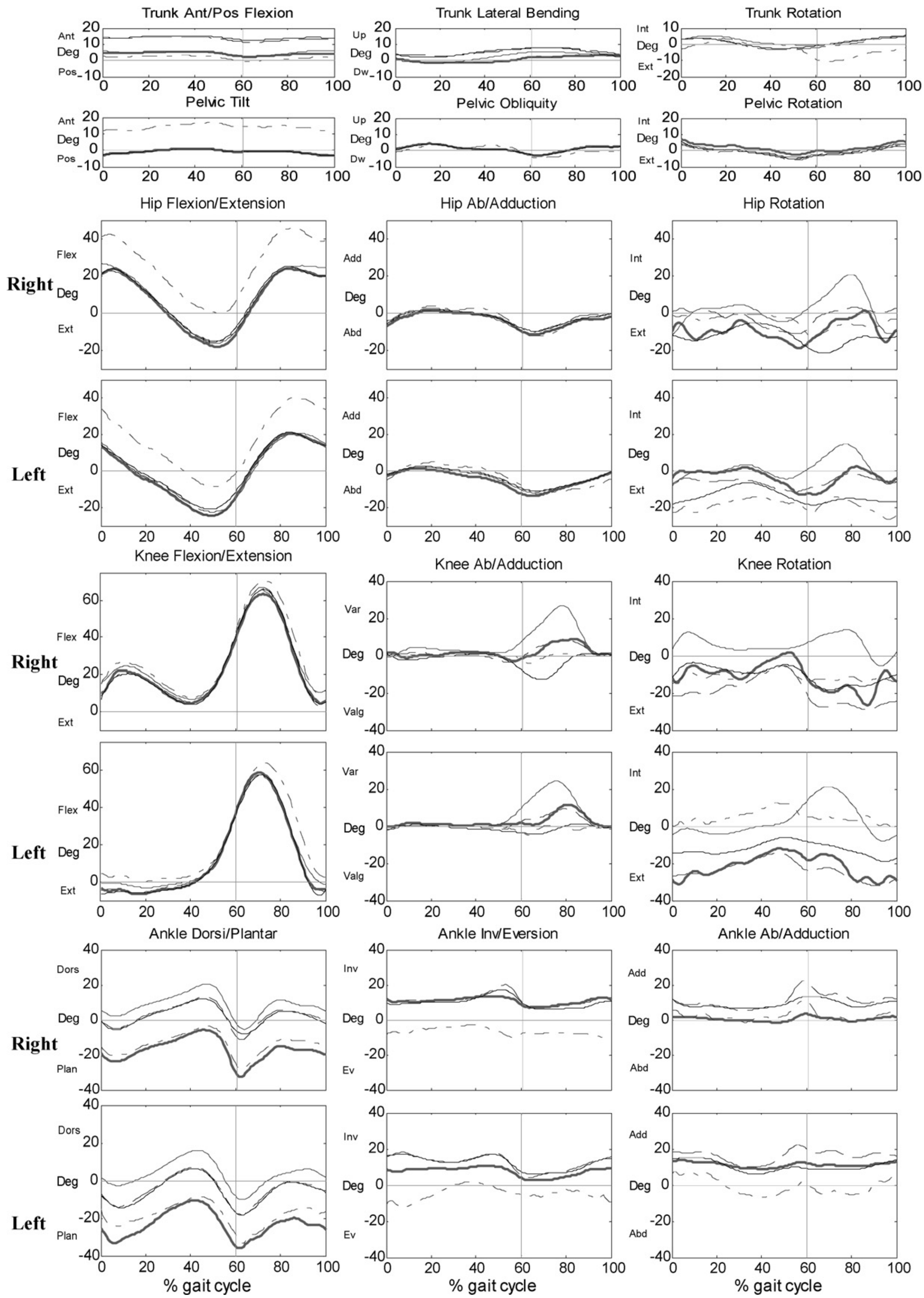

Fig. 3. Kinematics variables as calculated by the five protocols (line styles as in Fig. 2) and relative to only one complete gait cycle of subject AF. Trunk, pelvis, and right and left hips, knees, and ankles are reported over the rows; sagittal, frontal and transverse plane rotations over the columns. All five protocols reveal abnormal motion at the left knee (see Section 4 for more details).

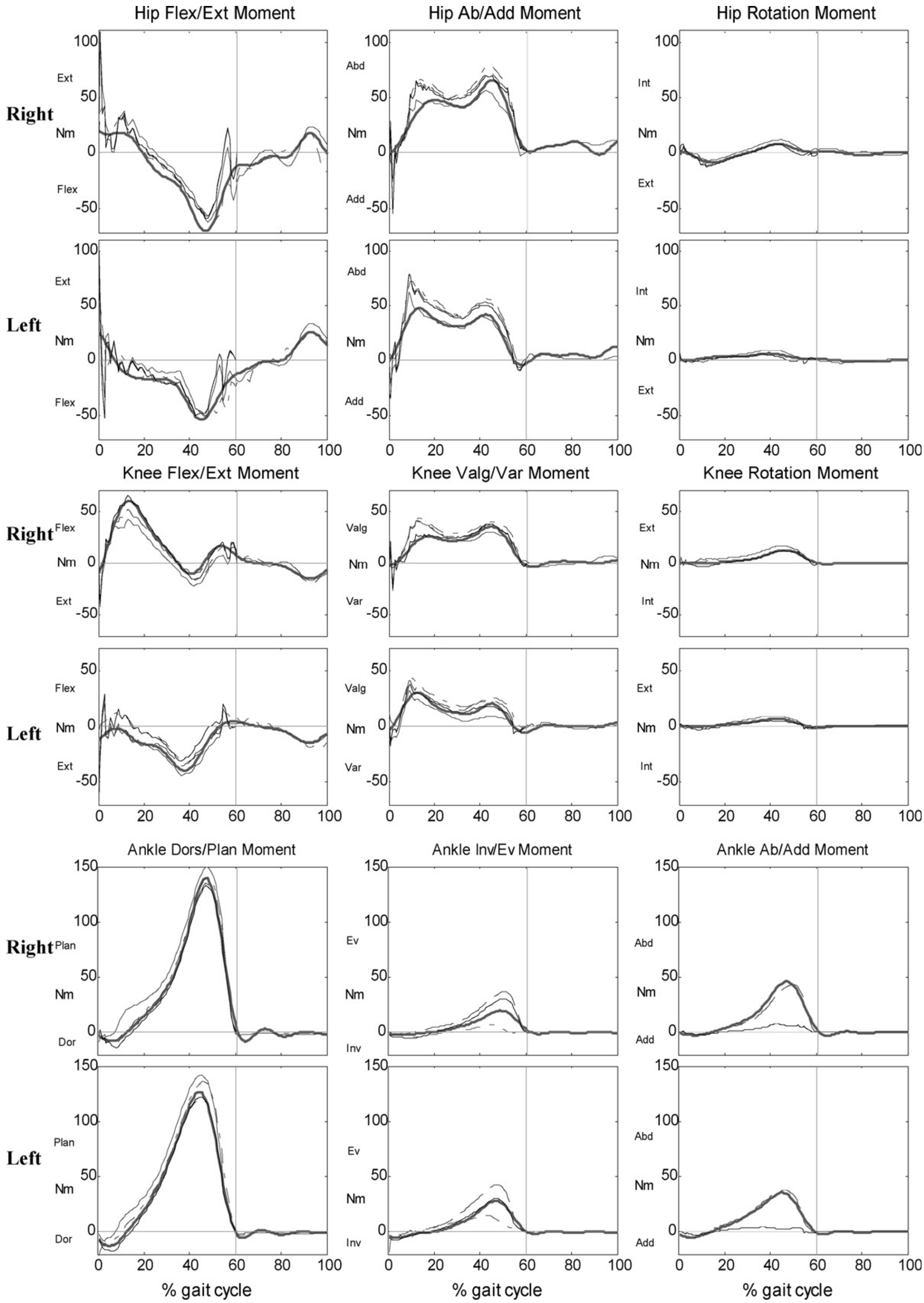

Fig. 4. Kinetic variables of subject AF, line styles as in Fig. 2. The convention adopted was that of the external moment, i.e. the resultant moment of the external forces.

Table 2
Inter-protocol variability across each joint rotation and moment obtained by merging in a single virtual curve the four trials of subject AF

	MAV Right	MAV Left	MRV% Right	MRV% Left
Rotations (°)				
Pelvic tilt	15.4		72.6	
Pelvic obliquity	1.9		19.0	
Pelvic rotation	3.6		16.6	
Hip flexion/extension	20.4	18.2	29.9	25.8
Hip abduction/adduction	6.1	8.2	30.4	32.4
Hip internal/external rotation	17.0	21.0	38.1	47.2
Knee flexion/extension	5.8	7.7	8.4	10.8
Knee abduction/adduction	11.9	7.5	27.2	23.7
Knee internal/external rotation	25.6	30.9	56.3	56.9
Ankle dorsi/plantarflexion	25.5	26.8	44.3	48.0
Ankle eversion/inversion	18.5	18.2	57.9	56.7
Ankle abduction/adduction	12.0	20.8	38.7	55.3
Moments [N*m]				
Hip flexion/extension	21.0	20.2	10.5	11.5
Hip abduction/adduction	18.1	16.9	13.5	13.2
Hip internal/external	4.2	2.5	17.3	23.7
Knee flexion/extension	15.0	15.0	13.2	18.2
Knee abduction/adduction	10.9	12.8	16.2	19.2
Knee internal/external	4.1	2.8	22.6	23.8
Ankle dorsi/plantarflexion	15.9	16.4	10.1	10.7
Ankle eversion/inversion	11.2	13.3	28.5	26.0
Ankle abduction/adduction	13.2	12.7	27.6	29.2

The maximum minus minimum value at each sample averaged over all samples (MAV) and the same normalised by the range of excursion of the relevant mean curve (MRV%) are reported for each variable.

left legs were not fully consistent within this subject. Very similar results were found for the other two subjects analysed.

When analysing the kinematic results of the patient in which abduction/adduction at the right knee was restrained by the joint prosthesis (SZM, Fig. 5) the results from the PiG protocol were the most critical, with a range of about 35°. T3Dg, SAFLo, CAST and LAMB contained mean error within 2.5° (Table 3).

Not a single couple of protocols emerged to be the most correlated (Table 4 for subject AF) in no one of the two subjects. Negative values, particularly in rotations out-of-the-sagittal planes, reveal opposite trends. Good correlations between protocols were found for the kinetics variables, the largest being ankle dorsi/plantarflexion ($r > 0.988$, $p < 0.001$). As for the kinematics variables, correlations were found smaller for rotations out-of-sagittal planes than for flexion/extensions. The correlation coefficient r for these latter was never smaller than 0.993 ($p < 0.001$) for the hip, 0.992 ($p < 0.001$) for the knee and 0.957 ($p < 0.001$) for the ankle joints.

Table 3
Mean and standard deviations of knee abduction/adduction along the three trials for subject SZM

	T3Dg	PiG	SAFLo	CAST	LAMB
Mean	2.2	8.1	0.7	1.3	2.5
Standard deviation	1.2	8.2	1.0	1.5	2.2

4. Discussion

Frequently, gait analysis results are interpreted and compared with limited consciousness of the conceptual and practical choices implied in the relevant protocol. In the present study, single gait cycles were analysed simultaneously by using five different protocols, which represent the large majority of those commonly used in gait analysis. Conformity with the original protocol design, i.e. biomechanical interpretation and marker-set, was ensured by direct participation of relevant experts, involved both in data collection and reduction.

The overall procedures were repeated in only three volunteers. However, the analyses of the right and left legs imply distinguished experiments, involving independent landmark identification, marker attachment, anthropometric measurement and data processing. In addition, subject SZM had a special knee prosthesis in only one leg. Finally, it turned out that subject AF had congenital leg length discrepancy (about 4 cm), which resulted in considerably different patterns between legs. Therefore, the present study should be regarded as composed by independent analyses of three trunks and pelves and six legs.

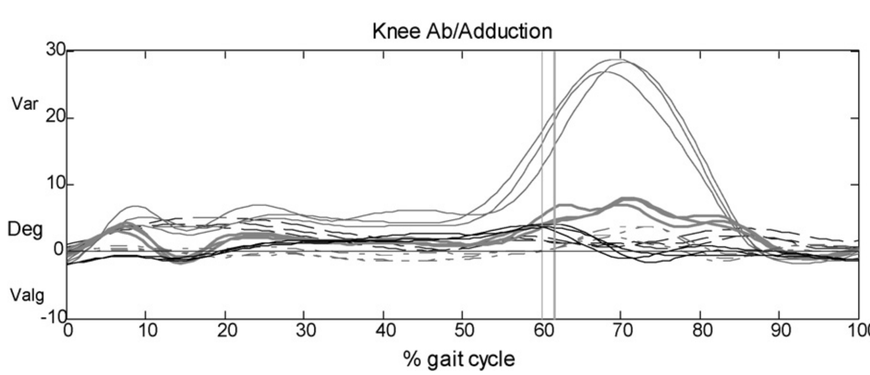

Fig. 5. Abduction/adduction at the right knee of subject SZM, as calculated by the five protocols over the three trial repetitions (line styles as in Fig. 2). In this joint, this rotation is fully restrained, therefore the gold standard for this variable is zero.

Table 4
Correlation coefficients obtained by comparing each couple of protocols and averaged over the four trials. These are reported for the right and left legs separately and for each joint rotation and moment variable

Protocols	T3Dg vs. PiG	T3Dg vs. SAFLo	T3Dg vs. CAST	T3Dg vs. LAMB	PiG vs. SAFLo	PiG vs. CAST	PiG vs. LAMB	SAFLo vs. CAST	SAFLo vs. LAMB	CAST vs. LAMB	T3Dg vs. PiG	T3Dg vs. SAFLo	T3Dg vs. CAST	T3Dg vs. LAMB	PiG vs. SAFLo	PiG vs. CAST	PiG vs. LAMB	SAFLo vs. CAST	SAFLo vs. LAMB	CAST vs. LAMB
	Right side										Left side									
Rotations (°)																				
Pelvic tilt	0.984***	0.838***	0.986***	0.977***	0.825***	0.989***	0.970***	0.835***	0.841***	0.988***										
Pelvic obliquity	0.998***	0.732***	0.991***	0.998***	0.727***	0.991***	0.994***	0.802***	0.739***	0.991***										
Pelvic rotation	0.996***	0.980***	0.989***	0.998***	0.978***	0.990***	0.990***	0.991***	0.980***	0.987***										
Hip flexion/ extension	0.997***	0.998***	0.999***	0.999***	0.994***	0.995***	0.998***	0.997***	0.997***	0.998***	0.998***	0.997***	0.999***	0.999***	0.999***	0.995***	0.996***	0.993***	0.994***	0.999***
Hip abduction/ adduction	0.998***	0.945***	0.994***	0.988***	0.946***	0.994***	0.986***	0.963***	0.981***	0.994***	0.999***	0.924***	0.996***	0.989***	0.929***	0.997***	0.985***	0.950***	0.866****	0.976***
Hip internal/ external	0.241	−0.055	−0.184	0.686***	−0.207	−0.182	0.646***	0.847***	0.111	0.137	0.467***	0.102	0.246	0.796***	0.472**	0.007	0.151	0.720***	0.321	0.641***
Knee flexion/ extension	0.995***	0.994***	0.999***	0.998***	0.994***	0.996***	0.997***	0.995***	0.995***	0.999***	0.998***	0.993***	0.999***	1.000***	0.994***	0.997***	0.999***	0.992***	0.993***	0.999***
Knee abduction/ adduction	0.869***	−0.108	−0.258	0.905***	−0.367	−0.567***	0.792***	0.741***	0.076	−0.046***	0.952***	0.027	−0.029	0.887***	−0.159*	−0.303**	0.740***	0.553***	0.147	0.317**
Knee internal/ external	−0.164	0.847***	0.768***	0.878***	−0.176	−0.089	−0.168	0.700***	0.798***	0.855***	−0.020	0.811***	0.855***	0.870***	0.137	0.337*	0.357*	0.843***	0.803***	0.887***
Ankle dorsi/ plantarflexion	0.984***	0.988***	0.988***	0.987***	0.987***	0.980***	0.992***	0.977***	0.984***	0.978***	0.975***	0.961***	0.996***	0.984***	0.981***	0.970***	0.980***	0.961***	0.957***	0.980***
Ankle eversion/ inversion		−0.032	0.971***	0.770***				0.090	0.338**	0.741***		−0.051	0.979***	0.850***				−0.066	0.339*	0.856***
Ankle abduction/ adduction		0.817***	0.926***	0.679***				0.797***	0.736***	0.717***		0.422***	0.702***	0.665***				0.880****	0.878***	0.909***
Moments [N m]																				
Hip flexion/ extension	0.967***	0.866***	1.000***	0.870***	0.921***	0.969***	0.897***	0.868***	0.960***	0.873***	0.939***	0.750****	1.000***	0.765***	0.868***	0.935***	0.833***	0.747***	0.702***	0.763***
Hip abduction/ adduction	0.968***	0.978***	1.000***	0.946***	0.955***	0.967***	0.941***	0.976***	0.975***	0.942***	0.979***	0.971***	1.000***	0.926***	0.982***	0.979***	0.938***	0.968***	0.983***	0.923***
Hip internal/ external	0.975***		0.977***	0.979***		0.944***	0.978***			0.951***	0.927***		0.879***	0.976***		0.825***	0.931***			0.834***
Knee flexion/ extension	0.970***	0.930***	0.991***	0.932***	0.952***	0.979***	0.904***	0.968***	0.952***	0.950***	0.976***	0.798***	0.969***	0.850***	0.864***	0.940***	0.882***	0.789***	0.968***	0.826***
Knee abduction/ adduction	0.968***	0.974***	0.932***	0.929***	0.932***	0.842***	0.860***	0.922***	0.952***	0.950***	0.945***	0.968***	0.983***	0.933***	0.968***	0.972***	0.919***	0.980***	0.986***	0.939***
Knee internal/ external	0.969***		0.966***	0.978***		0.958***	0.955***			0.977***	0.961***		0.963***	0.987***		0.916***	0.968***			0.939***
Ankle dorsi/ plantarflexion	0.994***	0.998***	1.000***	0.995***	0.996***	0.992***	0.988***	0.998***	0.993***	0.996***	0.997***	0.995***	1.000***	0.998***	0.997***	0.995***	0.993***	0.995***	0.996***	0.998***
Ankle eversion/ inversion		0.712***	0.992***	0.977***				0.753***	0.729***	0.987***		0.738***	0.996***	0.985***				0.740***	0.678***	0.990***
Ankle abduction/ adduction			0.942***	0.985***						0.958***			0.860***	0.994***						0.841***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Intra-protocol variability was small for all five protocols. This implies that intra-subject repeatability over the trials, however small in the three subjects analysed, was reported consistently over the protocols. In addition, the comparison of values in Tables 1 and 2 shows that inter-protocol variability is clearly larger than intra-protocol variability, except for pelvis rotation.

Overall the gait variables are comparable among protocols (Fig. 3), despite the large differences between models and marker-sets. Joint kinematics showed larger inter-protocol differences than joint kinetics. Flexion/extension had good waveform correlations with small bias differences in all joints except the ankle. On the contrary, out-of-sagittal plane rotations, especially at the knee and ankle joints, revealed poor waveform correlations and even considerable bias differences. The largest variability was observed at knee abduction/adduction where even opposite trends were observed. The extent to which this is due to the different models, marker-set or to relevant skin artefact is not known. Because similar patterns were observed over the six knees, it is hypothesized that a bias associated to the axis of rotation and related cross-talk is more plausible than an erroneous positioning of the markers.

The large consistency observed for the joint moments is noteworthy because of the known substantial differences between protocols about this calculation. LAMB, SAFLo and PiG use standard inverse dynamics, whereas T3Dg and CAST use only the external ground reaction force. Estimation of the joint centres is also very critical, and each protocol uses different techniques. This acceptable coherence on the results may further support the role of the external force, which must be predominant in gait at natural speed.

The PiG, based on the original Newington model, and SAFLo are among the pioneering protocols for gait analysis. When these were devised, basic instrumentation and limited knowledge of the skin artefacts were available. Therefore, it is remarkable that these protocols have obtained adequate correlation with the more recent ones for most of the gait variables. Bias and correlation differences of SAFLo are straightforwardly accounted for the specific anatomical references particularly for the pelvis and the ankle. T3Dg is a recent development of the general CAST approach. The very similar relevant results support further the fact that a small deterioration of the results is expected when the location of markers in the central area of the segments and calibration of landmarks via an instrumented pointer are substituted with direct skin marker placement. T3Dg and LAMB protocols share most model definitions except the equations for hip joint centre estimation (according to Refs. [35] and [8], respectively). Slightly different choices are adopted also for the marker-set, but all this did not result in considerable final differences for the gait variables. Overall, the high correlation obtained for the variables calculated by CAST, LAMB and T3Dg (Table 4) suggests that a large uniformity of the results is associated more to the consistency of the biomechanical conventions than to the design of the relevant marker-sets.

The abduction/adduction of the right knee of subject SZM (Fig. 5 and Table 3), i.e. the gold standard, revealed a considerably different performance of PiG with respect to the other protocols, though limited to the first half of the swing phase. This might have been due to an incorrect marker location resulting in incorrect alignment of the axis of rotation and therefore in cross-talk from flexion/extension, relatively large in that phase, to abduction/adduction. However, most of these markers are shared by the other protocols. In addition, a predisposition to larger abductions at the knee for this protocol was reported for all six knees. A larger variability for the joint rotations that require careful alignment of the wands was reported for this protocol also elsewhere [5,30]. The best performance in assessing this gold standard was obtained by SAFLo. This protocol identifies the flexion axis of the knee with a functional approach [36], which is expected to reduce this cross-talk.

The above remarks are only preliminary accounts of the observed differences. A thorough and rational comparison of the five techniques is possible by looking at every single gait variable and by inferring relevant justifications for these. The task is however not easy because the time-history of each variable results from an intrigued interplay of reference definitions, kinematics conventions and artefactual motion.

In conclusion, the comparison of the results from the five protocols on the same gait cycles revealed first of all good intra-protocol repeatability. Despite the known large differences among the techniques, good correlations were observed for most of the gait variables. As for the exact variable patterns, good consistency was found for all joint flexion/extensions and pelvic rotations. Acceptable consistency was found for hip out-of-sagittal plane rotations and nearly all joint moments, whereas it was poor in knee and ankle out-of-sagittal plane rotations. For the latter therefore, it is recommended that comparison of the results among protocols be very careful. The variability associated to the protocol used seems much larger than that associated to inter-observer and even inter-laboratory comparisons [5,17,29,30] for most of the gait variables. It might be also pointed out that, in general, model conventions and definitions seem more crucial than the design of the relevant marker-sets, and that therefore sharing the former can be sufficient for worldwide clinical gait analysis data comparison.

Conflict of interest statement

The author states that there is no conflict of interests for the manuscript.

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