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Current practices in clinical gait analysis in Europe: A comprehensive survey-based study from the European society for movement analysis in adults and children (ESMAC) standard initiative

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ABSTRACT

Background: Clinical gait analysis (CGA) is a systematic approach to comprehensively evaluate gait patterns, quantify impairments, plan targeted interventions, and evaluate the impact of interventions. However, international standards for CGA are currently lacking, resulting in various national initiatives. Standards are important to ensure safe and effective healthcare practices and to enable evidence-based clinical decision-making, facilitating interoperability, and reimbursement under national healthcare policies. Collaborative clinical and research work between European countries would benefit from common standards.
Research objective: This study aimed to review the current laboratory practices for CGA in Europe.
Methods: A comprehensive survey was conducted by the European Society for Movement Analysis in Adults and Children (ESMAC), in close collaboration with the European national societies. The survey involved 97 gait laboratories across 16 countries. The survey assessed several aspects related to CGA, including equipment used, data collection, processing, and reporting methods.
Results: There was a consensus between laboratories concerning the data collected during CGA. The Conventional Gait Model (CGM) was the most used biomechanical model for calculating kinematics and kinetics. Respondents

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also reported the use of video recording, 3D motion capture systems, force plates, and surface electromyography. While there was a consensus on the reporting of CGA data, variations were reported in training, documentation, data preprocessing and equipment maintenance practices.
Significance: The findings of this study will serve as a foundation for the development of standardized guidelines for CGA in Europe.

1. Introduction

Walking is a complex motor activity involving the coordination of multiple body segments and muscles. Various neurological, musculoskeletal, or systemic disorders often lead to abnormalities during gait which may significantly affect an individual's functional ability and quality of life. Clinical gait analysis (CGA) serves as a systematic approach to comprehensively evaluate gait patterns, quantify impairments, plan targeted interventions to improve gait, and evaluate the impact of interventions. CGA, also referred to as three-dimensional instrumented gait analysis, instrumented gait analysis, or simply gait analysis, is defined as "the process of recording and interpreting biomechanical measurements of walking in order to support clinical decision-making in case of gait dysfunction" [1]. The clinical effectiveness of CGA has been established in its ability to assess and manage gait abnormalities in various patient populations [2].

Standards in medical practice are crucial for the clinical evaluation of various aspects of healthcare. Through standards, safety, effectiveness, and quality of medical practices are guaranteed. Standards provide a consistent approach to clinical evaluation, ensuring that assessments are conducted uniformly across laboratories in different countries, and facilitate interoperability. By promoting the use of evidence-based medicine, the quality of the health care services standards can be improved, and the possibility of receiving reimbursement from national funding bodies can be increased. For instance, the American Clinical Neurophysiology Society has proposed a set of 7 guidelines for the clinical use of electroencephalography (EEG) [3] that include, among others, guidelines for minimum technical requirements for performing clinical EEG, a standard electrode position nomenclature, and guidelines for writing EEG reports.

Currently, CGA has no established guidelines at international or European level. However, several regional initiatives have emerged. The Clinical Movement Analysis Society (CMAS) from UK and Ireland have standards and guides for new and existing CGA laboratories in their countries (available on their website [4] and a recent publication [5]). CMAS accredits clinical gait analysis laboratories by auditing them according to these standards and publishes accredited laboratories on their website. Today, 15 laboratories are accredited. Standards are updated based on best evidence and technological advances, following the consensus of members. Changes are made following the consensus of members. Similarly, the North American Commission for Motion Laboratory Accreditation (CMLA) proposes to accredit CGA laboratories based on their standards [6]. In 2017, the Italian Society of Clinical Movement Analysis (SIAMOC) published a position paper on CGA based on the results of an Italian consensus conference [7]. They have formulated several statements according to 13 questions in three areas based on scientific evidence or experts' opinion. These areas are (1) general requirements and management, (2) methodological and instrumental issues, and (3) scientific evidence and clinical appropriateness. The Australia and New Zealand Clinical Motion Analysis Group (ANZ-CMAG) has recently proposed clinical practice recommendations for CGA based on the experience of 7 laboratories. These recommendations take into account a wide range of CGA dimensions, from staff training, data acquisition to the interpretation of results. These recommendations are themselves based on existing recommendations, mainly from CMAS, CMLA and literature reviews. However, the methodology for creating this standard is not described in the article, nor is how it will be updated. There are also several initiatives underway by national clinical gait analysis societies (France: Société Francophone d'Analyse du Mouvement chez l'Adulte et l'Enfant - SOFAMEA - systematic review to propose metrological recommendations [8], Netherlands & Belgium: Society for Movement Analysis Laboratories in the Low Lands - SMALLL, Germany, Switzerland, Austria: Die Gesellschaft für die Analyse Menschlicher Motorik in ihrer klinischen Anwendung GAMMA [9]) but official results are still pending. Previous European research projects have attempted to propose standards, such as Computer Aided Movement Analysis in a Rehabilitation Context - CAMARC [10], CAMARC II [11], and Model-Driven European Pediatric Digital Repository -MD-PAEDIGREE [12] but their results have not been adopted as a standard by the CGA community. The reasons for the failure of these two European initiatives to establish a CGA standard are unclear. Some factors that might have contributed are: the lack of accessible and authoritative sources (documents, articles, websites) that could define the standard, the insufficient dissemination of information about the standard, lack of involvement of enough laboratories to develop the standard, the absence of consultation with scientific societies and/or the overly broad and vague scope of the projects in relation to standardization.

Some guidelines were also proposed considering specific components of CGA. For example, the International Society of Biomechanics (ISB) has established recommendations for kinematic model definition, including a methodology for calculating joint kinematics and kinetics [13–15]. Similarly, the European Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles - SENIAM project has established a protocol [16] for electromyographic (EMG) sensor placement and data reporting which is well recognized and used scientifically and clinically. In 2019, the Consensus for Experimental Design in Electromyography (CEDE) project took over to guide decision-making in EMG recording, analysis, and interpretation [17]. Currently, there are recommendations on the terminology of EMG [18], the selection of electrodes [19], the amplitude normalization [20], the use of high-density sensors [21] and their applications [22].

There is significant potential value in harmonizing the approach to CGA at least across European countries, in particular, in establishing standards for CGA which could be adopted by the entire community. Based on this observation, the European Society for Movement Analysis in Adults and Children (ESMAC) which oversees and works in close collaboration with the European national societies (CMAS, GAMMA, SIAMOC, SMALLL, SOFAMEA) has begun working on CGA standardization following three consecutive steps. The first step entailed identifying the needs and scope of CGA standards and evaluating whether laboratories would be interested in participating in an initiative to define such standards. This survey was completed in 2020 [23]. With more than 185 responses, the results demonstrated a significant need to define standards for CGA and that laboratories are ready to participate. The second step is to establish an overview of current practices of CGA in Europe. The presentation of the methodology and results of this step are addressed in this study. The third step will define CGA Standards based on the use of a modified Delphi process.

Therefore, the aim of this study is to review current laboratory practices for CGA in Europe and to set the ground for the proposed Delphi process.

2. Method

2.1. Survey preparation

To define the main topics of interest for the survey, the following national European societies (in alphabetic order) were contacted: CMAS, GAMMA, SIAMOC, SMALLL, and SOFAMEA. Each society circulated a "call for interest" to participate in formulating the questions for the survey and a working group of 19 individuals with different backgrounds (i.e., clinicians, physiotherapists, engineers, laboratory technicians, movement scientists) was formed. We decided to construct our questionnaire mainly based on the standards and consensus on clinical gait analysis created by the national societies. We therefore formed a subgroup to extract the questions from the CMAS standard and a group to extract the questions from the SIAMOC consensus. In addition to these two subgroups, we created a subgroup to manage all the processes. We also created a subgroup working more specifically on new technologies, which are increasingly present in the analysis of human movement, and a final subgroup working on the clinical aspect of CGA. Therefore, in total, five subgroups were defined: (1) management, (2) CMAS, (3) SIAMOC, (4) new devices, and (5) clinical aspects (Table 1).

The *management group* was responsible for defining the tools to fill in the questionnaire, harmonizing all questions, and coordinating the distribution of the questionnaire, ensuring smooth and efficient communication throughout the process.

The *CMAS group* was tasked with defining questions that would be useful for the creation of the European CGA-standards by using the CMAS standards as a guideline [5].

The *SIAMOC group* shared a similar responsibility with the CMAS group, which involved extracting relevant questions from the SIAMOC consensus paper [7].

The *new devices group* drafted questions related to new devices that might be used in the different CGA labs, such as markerless motion tracking, activity monitors and inertial measurement units (IMUs).

Lastly, the *clinical group* defined questions related to the clinical relevance and interpretation of CGA, the definition of CGA, and additional measurements that are performed as part of a CGA, such as plantar pressure measurements and energy expenditure.

Once each group finalized a version of their questions, the questions were discussed in the management group and modifications were made if needed. Each group discussed the suggested changes and created a new version of the questions. This process was repeated until a consensus was reached on each question. This resulted in a total of 75 questions, that were divided into five categories: (1) General information and management (n = 22), (2) Facility and instrumentation (n = 14), (3) CGA data acquisition (n = 11), (4) CGA data processing (n = 13), and (5) CGA data reporting (n = 15). All questions are available in the supplementary materials in the file *Survey_ESMAC_Questions.pdf*.

2.1.1. General information and management

In this category, general information about the participating laboratories was collected. Two questions contained sensitive information that will not be disclosed. In particular, the following aspects were considered: geographical distribution of the laboratories involved in the survey, type of institution, laboratories' staff (i.e., head of the lab, country of origin of the staff, professional profiles), management (i.e., frequency of staff training, costs), accreditation (i.e., license to conduct gait analysis, guidelines), and population characteristics assessed in gait laboratories (i.e., neurological, non-neurological, age, patient throughput).

2.1.2. Facility and instrumentation

Information included the following aspects of the facilities and instrumentation: laboratory dimension, facility, equipment (i.e., 3D motion capture system, video cameras, force plates, EMG, others), certification (i.e., CE certification), technical aspects (i.e., testing consistency, measure frequency, synchronization of the devices), and quality control (i.e., equipment check, external technical calibration, external quality control, documentation, auditors).

2.1.3. CGA, data acquisition

The following methodological features of CGA were considered: general CGA aspects (i.e., time to conduct CGA), type of data collected (i.e., kinematics, video footage, ground reaction forces, kinetics, muscle activation), additional measures to CGA, acquisition check (i.e., during/after acquisition, minimum number of steps/gait cycles), recommendation and standards used, reporting (i.e. information included in the report, visualization), normative data, CGA models (i.e., published models, self-developed models, inclusion of upper body, wand, clusters), and CGA data for decision making (i.e., identifying gait deviations), information to patients.

2.1.4. CGA, data processing

This category examined data processing techniques in CGA including: data preparation (i.e., gait event detection, gap filling in the trajectories), filtering (i.e., marker trajectories, joint angles, EMG, force plates), and processing (i.e., biomechanical computation). The use of advanced methodologies (i.e., computational modeling) was also investigated.

2.1.5. CGA, data reporting

Information on data reporting included: software for reporting,

Table 1
The people who participated in the working group to prepare the survey and their allocation.

Name	Society	Expertize	Group/Task
Stéphane Armand	ESMAC	Movement scientist, Gait laboratory manager	Management of the survey
Ann Hallemans	SMALLL	Movement scientist	
Florent Moissenet	SOFAMEA	Engineer	
Zimi Sawacha	ESMAC	Engineer, Gait laboratory manager	
Isabella Campanini	SIAMOC	Physiotherapist, Gait laboratory manager	Extract questions from the SIAMOC consensus
Michela Cosma	SIAMOC	Physician	
Annamaria Guiotto	SIAMOC	Engineer	
Andrea Merlo	SIAMOC	Engineer, Gait laboratory research manager	
Maurizio Petrarca	SIAMOC	Physiotherapist, Gait laboratory manager	
Fabiola Spolaor	SIAMOC	Kinesiologist	
Harald Böhm	GAMMA	Gait laboratory manager	Extract questions from the CMAS standards
Colm Daly	CMAS	Senior Physiotherapist, Gait and movement analyst	
Andreas Kranzl	GAMMA	Sport scientist, Gait laboratory manager	
Heather Read	CMAS	Consultant Orthopaedic Surgeon	
Herwin Horemans	SMALLL	Movement scientist, Gait laboratory manager	Define questions concerning new technologies
David Gasq	SOFAMEA	Physician	Define questions concerning clinical aspects of CGA
Marije Goudriaan	ESMAC	Movement scientist	
Catherine Huenaerts	SMALLL	Physiotherapist, Gait laboratory manager	
Marjolein van der Krogt	SMALLL	Movement scientist, Gait laboratory manager	

anthropometric measures, normative bands (i.e., comparison with normative bands yes/no, characteristics of normative data), kinematics (i.e., joint angles, spatiotemporal parameters), kinetics (i.e., joint torques, force data), EMG, other measures (i.e., physical examination, clinical scales).

2.2. Data collection

Once we finalized the questions, they were transferred to SurveyMonkey. The questionnaire was sent to all ESMAC members and the members of the national societies in Europe on 2nd February 2021. We sent a reminder on 3rd March 2021 to ensure we would receive a maximum number of completed questionnaires. The deadline to complete the questionnaire was set at 15th March 2021.

2.3. Data processing

We consolidated all completed questionnaires into a single file. Subsequently, we eliminated duplicate laboratory entries, retaining the most comprehensive responses when multiple individuals had provided answers for the same laboratory. We also eliminated answers from laboratories not based in the EU (except for the UK and Switzerland, the UK was still part of the EU when this process was started), as well as confidential information.

The questionnaire contained several free text inputs. Three authors (SA, MSa, BH) checked these inputs and curated the answers, so they could be used for further analyses. For example, when a range was given while a unique value was required, the average value of that range was used. The details of all modifications can be found in the sheet *Modification_track* in the file *Survey_ESMAC_Data.xlsx* in the supplementary materials and in the data deposit [24].

The final version of the (curated) dataset (sheet *Data4Processing* in file *Survey_ESMAC_Data.xlsx)* was used as input in a custom-written R-based code (R software package information, version 4.2.1) to analyze the outcomes of the questionnaire. This code can be freely downloaded in the supplementary materials (file *Survey_ESMAC_RCode.Rmd*) and in the data repository [24]. The anonymized raw data, and the curated dataset used for the analyses, can be found in the supplementary materials (file *Survey_ESMAC_Data.xlsx)* and in the data deposit [24].

3. Results

Statistics and figures for the 75 questions of the survey are available as an HTML page in the supplementary material (file *Survey_ESMAC_Results.html)*. Results for a subset of the questions are presented in the following sections. The corresponding question numbers are quoted with the following format: [Q1] for the first question and so on.

3.1. General information and management

We collected data from 97 respondents, one respondent per gait laboratory, from 16 different countries [Q2] (Fig. 1). The majority of the gait laboratories are hosted within hospitals (54%), rehabilitation centers (23%), and universities (12%) [Q4] (Fig. 1). Most gait laboratories conduct between 200 and 1000 separate visits in the last five years (between 40 and 200 per year [Q5]). Many of these visits are to conduct CGA [Q5–6] in both adults and children (59%), solely adults (25%), and solely children (15%) [Q7]. The main neurological conditions assessed are cerebral palsy, neuromuscular diseases, and stroke [Q8, Q10] and the main non-neurological conditions are trauma, arthrosis, and spinal deformities [Q9, Q11].

When charged, the cost of a CGA visit varies between 100 and more than 2000 EUR, [Q13]). The median times to perform the following key aspects of the CGA are: 20 min for subject preparation, 30 min for data collection, 30 min for data analysis, and 20 min for report generation, summing up to a median total of 100 min, excluding the physical examination (median: 30 min) [Q22]. More than 90% of the survey participants indicated that gait laboratory personnel are involved in CGA data collection, processing, analysis, and interpretation. Additionally, 80% reported gait laboratory personnel involvement in clinical examinations, while 68% and 70%, respectively, are engaged in the decision-making processes related to conducting a CGA and clinical decision-making [Q19]. A wide range of professions lead the technical and/or clinical aspects of a gait laboratory, the most prevalent is clinical technologist (31%) for the technical lead and physical and rehabilitation medicine doctor (28%) for the medical lead [Q18]. Gait laboratory

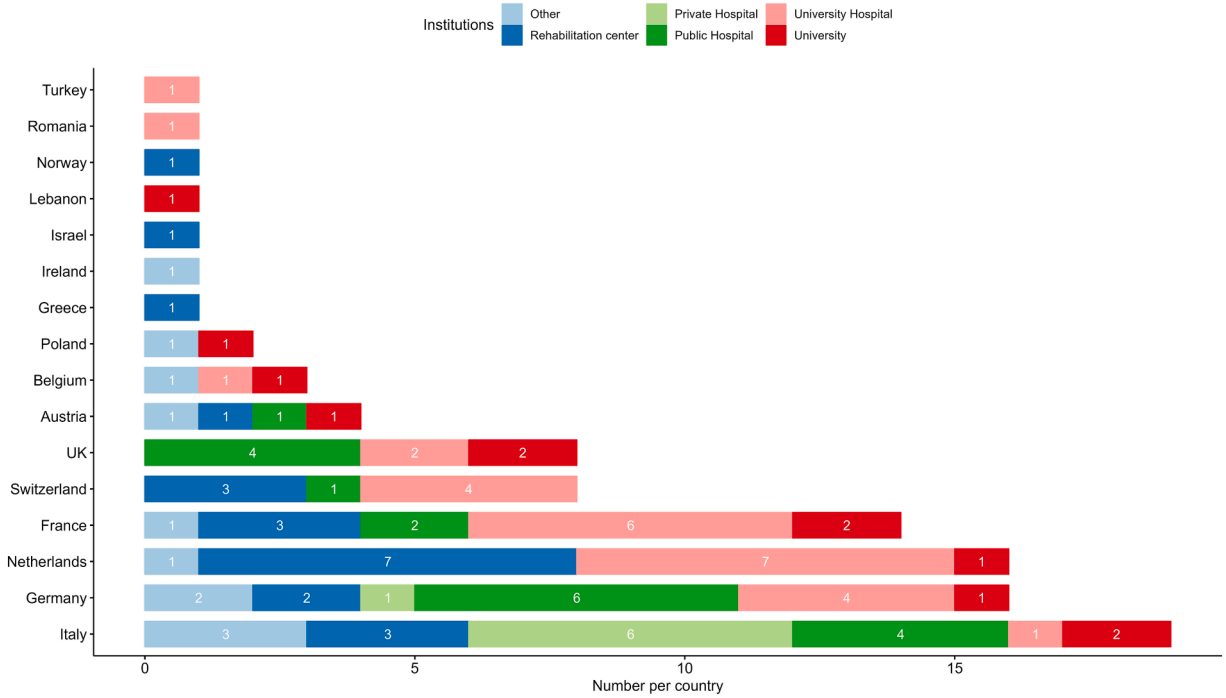

Fig. 1. Respondent countries [Q2]: the countries of origin of the respondents. Additional grouping depending on the type of institutions.

personnel receive regular training for the main tasks associated with CGA, about 40% of laboratories offer training to their staff at least every two years.

3.2. Facility and instrumentation

Laboratories have the following facilities in more than 90% of the cases: daily floor cleaning, leveled floors, adequate seating options, separated changing rooms, controlled room temperature, and controlled access to the room with facilities for patients with disabilities [Q24]. The median size of the labs is 12.5 m in length, 6 m in width, and 3 m in height [Q23].

The most commonly used devices include video cameras (median frequency of data acquisition: 50 Hz), 3D motion capture (100 Hz), force plates (1000 Hz), and surface EMG devices (1000 Hz) and are CE certified [Q26]. These devices are generally synchronized in over 90% of the labs [Q25-Q28]. During CGA, the most frequently collected data (considering the sum of categories "Always" and "Often") are video recordings (71%), lower limb kinematics (84%), lower limb kinetics (77%), and surface EMG (56%) [Q29]. Additionally, a physical examination is generally conducted (67%) [Q29] (Fig. 2). The median minimum number of gait cycles considered necessary to satisfactorily interpret CGA is 6 for spatio-temporal parameters and kinematics, and 5 for kinetics and surface EMG [Q31].

Regarding the quality control of equipment, few laboratories have an external technical calibration once a year (around 10%) or at the opening of the laboratory (around 35%) [Q32]. A significant portion of laboratories (ranging from 26% to 39%) never perform quality control of their equipment [Q33]. Only a small number of laboratories (less than 16%) have external quality control each year [Q33].

The availability and content of documented laboratory operational procedures for CGA are heterogeneous. More than 75% of laboratories have the following items described in their operating procedures: calibration, equipment functionality, marker placement, marker attachment, EMG skin preparation, EMG placement, and patient instructions [Q34]. This documentation is mostly available in electronic format (91%), stored in a folder within the laboratory (70%), and is revised after a defined period (48%) [Q35]. However, most laboratories do not conduct audits of their documentation, either internally (74% of the laboratories), nor externally (64%) [Q36].

3.3. CGA, data acquisition

Before starting a new acquisition, most laboratories check the quality of the overall performance of the equipment: starting from the calibration of the 3D motion capture system (93%) and the visibility of the markers (91%) up to the presence of offset in the force plates (88%) and the quality of both the EMG (87%) and the video signals (84%). Only a lower percentage of laboratories perform a further check on the EMG signals for identifying the presence of crosstalk (56%) [Q37] (Fig. 3). During the acquisitions, most laboratories check the visibility of the markers, foot strike on the force plate, and loss of both EMG and force plate signals (86%-95%). Furthermore, the presence of noise is considered by a large percentage of laboratories (80%), while approximately half of the respondents consider the saturation of the force plate signals (56%) [Q38]. After data acquisition and before the patient leaves the laboratory , the majority of the laboratories check the number of foot strikes on the force plates (93%), loss of marker visibility (86%), or force plate signals (82%). A slightly lower percentage of respondents check the loss of EMG signals (77%) [Q39].

3.4. CGA, data processing

The different steps for data preparation that are always performed by at least 50% of the respondents are: event detection (checked manually), gap filling of marker trajectories, smoothing marker trajectories and force place signals, and filtering EMG signals [Q41]. Event detection is executed mainly with force plates (30% of the respondents), Zeni's method (24%), or manually (20%) [Q42a]. The most often used software is Nexus (Vicon) at 48%, followed by Matlab (19%). Most respondents (71%) reported using the conventional gait model (CGM [25]), and 5% did not know which model they used [Q50a] (Fig. 4). Of those who use the CGM, 53% use the model with thigh and shank side wands (47% without) and 25% use the KAD for the alignment of the medio-lateral axis of the femur [Q49b, 49c]. A large majority of respondents use predictive methods to locate the hip joint centers (85% after removing those who reported non-applicable (NAs)), the femoral epicondyles and tibial malleoli to locate the knee and ankle centers and axes (64%), and tables for the body segment inertial parameters (92% after removing NAs) [Q51, 52, 53]. The kinematic and kinetic calculations are mainly run from Nexus (Vicon) 62%, with overlaps with Matlab (54%) and dedicated packages from Bodymech (5%), Dumas (5%),

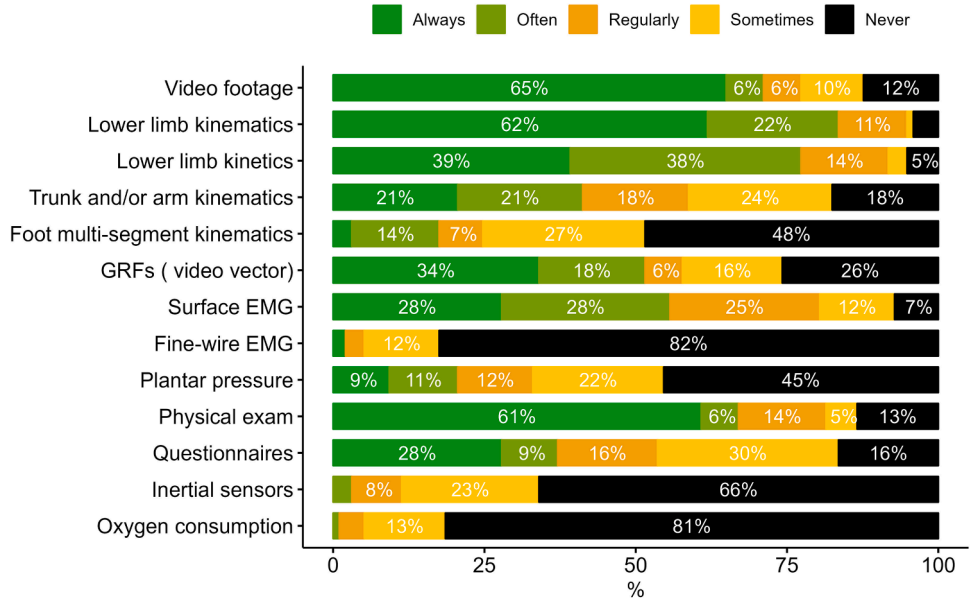

Fig. 2. Data collected [Q29]: Frequency of collection of different types of datasets during CGA.

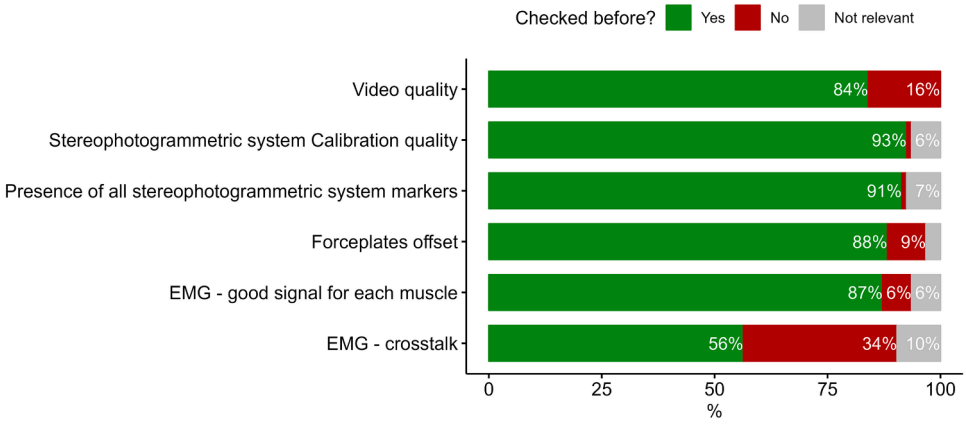

Fig. 3. Check equipment [Q37]: equipment checked before data acquisition.

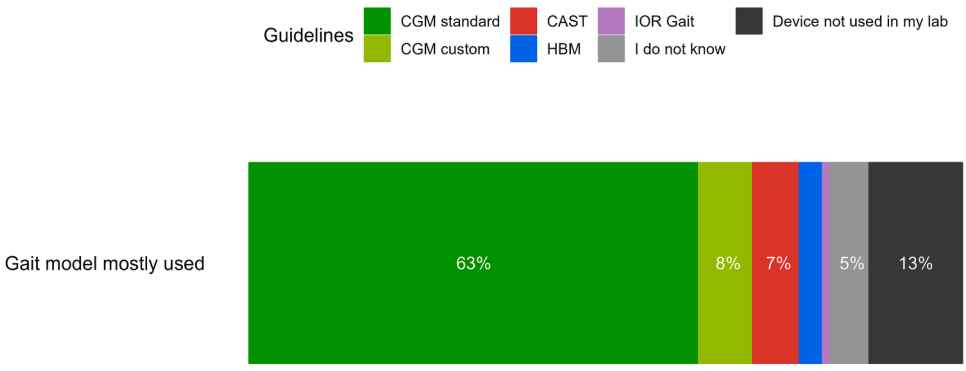

Fig. 4. Models used [Q50a]: Gait model most used in gait laboratories (CGM – Conventional gait model, CAST - Calibrated anatomical system technique, HBM - Human Body Model, IOR - 'Istituti Ortopedici Rizzoli Gait').

Python (18%), and the pyCGM2 dedicated package (7%) [Q59]. Advanced modeling, such as musculoskeletal modeling or muscle synergies is rarely performed (<20% of respondents). OpenSim is used by 7% of respondents for the kinematic and kinetic calculations [Q57]. Similarly, further processing of the EMG signal, such as envelopes or onset timing, is not commonly performed [Q55].

3.5. CGA, data reporting

The ISB recommendations [13–15] for the reporting of kinematic and kinetic data are only partially followed (63% of the respondents after removing NAs [Q58]). Respondents reported using Vicon (Polygon, 60%), their own Matlab code (54%), Visual 3D (12%), or their own Python code (12%), either solely or in combination, to prepare their technical gait analysis report [Q61] (Fig. 5). Ninety-five percent of

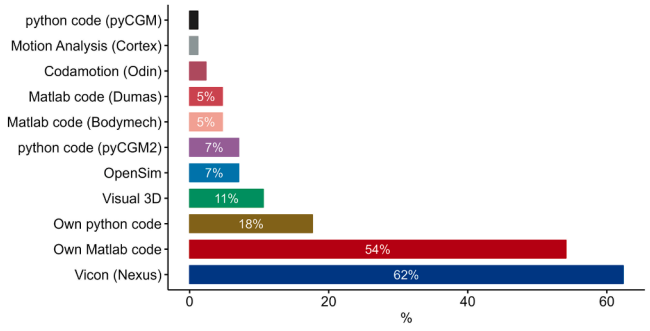

Fig. 5. Software biomechanical computation [Q59]: Software used by laboratories to create a report of clinical gait analysis data.

respondents use a technical report that presents the data recorded during CGA with varying details about the methods employed [Q56]. Eighty-four percent of respondents also provide a medical report that presents the medical interpretation of the technical report. In 53% of cases, multimedia data, including videos, are also reported [Q62]. The data included within reports vary between laboratories [Q64], and mainly includes spatio-temporal parameters (92%), kinematics and kinetics (93%, 89%), physical examination (86%), conditions of testing (94%), identification of body side (100%), normative values (91%), and the identification of the gait cycle (94%). Most respondents reported that normative data are collected in the laboratory (79%) with 45% reporting the use of age-matched values, 31% making comparisons to data from the literature, and only 8–10% using gender or speed-matched values [Q65]. From 73 respondents, the average number of subjects in the normative data are 46 (SD 28) [Q67]. The CGA report is delivered to the referring professional in 91% of cases, and to the patient always or sometimes in 89% of cases [Q69]. Medical history (74%), range of motion assessment (74%), and strength assessment (69%) are primarily and always used as additional clinical data for decision-making [Q70]. Between 69% and 82% of respondents reported that the raw and processed data and the report are stored on a local computer (69%), server (73%), or server with frequent backups (82%) [Q73]. Raw and processed data are stored for on average 23 (SD 22) years and the report for 27 (SD 26) years.

4. Discussion

This study aimed to review current laboratory practices for CGA in Europe. The primary motivation driving our study was the desire to devise harmonized and standardized practices for CGA. Therefore, it was

crucial to have a comprehensive understanding of the existing landscape before working towards a common standard. This study provides insights into current practices which will inform the development of common standards in the future.

Since the 1980s, CGA has undergone significant development, emerging as a valuable tool in clinical practice. It is now provided by a dedicated service as part of mainstream healthcare and it is generally integrated within the clinical governance structures of tertiary referral centers [1]. GGA advancements have enabled clinicians to better understand gait deviations and their causes. A recent systematic review by [2]. strongly supported the benefits of CGA in influencing treatment decisions, enhancing treatment-planning confidence, improving inter-clinician agreement, and ultimately enhancing patient outcomes [2]. For example, their review demonstrated that patients undergoing femoral derotational osteotomy surgery achieved superior outcomes when they received and followed CGA recommendations. Conversely, outcomes were inferior when the gait report was not received or received but not followed.

This study shows a good agreement on the equipment used in CGA, encompassing video cameras, 3D motion capture systems, force plates, and surface EMG devices. This alignment is also supported by narrative reviews in the respective fields [1,26], the SIAMOC position article that reported: "the minimum set of measurement systems are: stereophotogrammetry, force platforms and EMG" [7], and the clinical practice recommendations from the ANZ-CMAG group [27].

Our survey further shows that CGA is typically complemented by a physical examination including range of motion, strength, selective motor control and, where applicable, spasticity assessment. This clinical information supports the interpretation of the gait data [26,28].

The most frequently employed model for calculating kinematics and kinetics is the CGM, available through commercial software (e.g., Plug-in-Gait in Nexus, Vicon) as well as open-source platforms (such as pyCGM2) [29]. The CGM offers the benefits of simplicity and well-defined limitations [25].

Despite the use of the CGM, substantial variations in the application of the biomechanical model were observed across different laboratories. Notably, 47% of these laboratories do not employ lateral wands for the thigh and shank segments although a recent study showed that this may induce more errors, especially in children [30]. Only 25% of respondents opted to use a Knee Alignment Device. However, this device has been replaced in many laboratories by a medial knee marker known as the KAD-med variant of the CGM, available through pyCGM2 [29].

Although these variations may impact hip and knee rotation measurements, significant consistency exists among various gait models in the sagittal plane [31]. Alternative marker locations (e.g., patella for the thigh, tibial crest for the shank) may be better choices for the conventional gait model but none of the respondents explicitly answered they used alternative marker locations [32–36].

The alternative to commercial software is to use self-developed code using Matlab or Python (Matlab being the dominant choice in this survey). This approach provides the opportunity for creating custom solutions and incorporating the latest research advancements. However, it is important to note that there exists a potential risk of calculation errors, and the different codes across different laboratories could potentially influence the outcomes and compromise the interoperability between laboratories. It is crucial to establish a methodology in CGA standards that facilitates the seamless integration of the latest research discoveries into clinical practice. This methodology could draw upon COSMIN recommendations [37], which advocate for evaluating the psychometric properties of outcomes, including validity, repeatability, and sensitivity to change. By aligning with COSMIN guidelines, we can ensure a robust framework for assessing and incorporating advancements in CGA into clinical standards effectively. Moreover, CGA standards will have to integrate the new medical device regulation (MDR) which has been in effect in Europe since 26 May 2021, with a transitional extension until the end of 2028 [38]. Equipment and software (also now classified as a medical device) used for CGA must adhere to these recommendations. ESMAC and CMAS have published position statements on the impact of the MDR on CGA [39,40]. While the MDR introduces regulatory challenges to CGA practice, it also presents an opportunity to strengthen standards and ensure the seamless integration of research advancements into clinical practice. By adhering to established guidelines and remaining vigilant in equipment selection, laboratories conducting CGA can improve the quality of their service. Based on our survey data, a consensus exists among laboratories regarding the reporting of CGA data. In 75% of cases, CGA encompasses physical examination, non-normalized spatio-temporal data, kinematics of the lower limb and pelvis, kinetics of the lower limb normalized by body weight, and ground reaction forces. This information is presented for both the left and right sides. Furthermore, comprehensive coverage of various walking conditions is ensured. These data are consistently compared with normative data, often sourced from individual laboratories that agree with CMAS recommendations [5].

Ensuring high-quality CGA necessitates thorough training of the individuals conducting the assessments, documentation of procedures to maintain transparency and consistency, and periodic maintenance and calibration of equipment to uphold accuracy and reliability. The training of individuals conducting CGA is variable among the laboratories but performed in more than 90% for the main tasks associated with CGA (data collection, reduction, interpretation, marker placement, surface EMG electrode placement, and physical examination). Respondents reported that the reliability tests recommended by the CMAS [5] and the ANZ-CMAG [27] are rarely performed. Moreover, a significant portion of laboratories (around 30%) never conduct external quality control on their equipment increasing the risk of inaccuracies in the results. This finding can be attributed to various factors. The questionnaire asked for quality control by an external company, potentially overlooking internal metrological control procedures in some laboratories or hospitals. Additionally, the absence of clearly established European or international recommendations could have led to a lack of rigor in certain laboratories. Finally, respondents may lack precise knowledge of the quality control measures implemented in their laboratory.

The documentation of procedures varies according to the topics, but over 75% of the most crucial tasks of CGA data acquisition are documented (e.g., calibration, marker placement, EMG placement). However, these operating procedure documents are seldom audited, either internally or externally, and updated.

Writing documents and protocols detailing all the information are very important in the standards process (staff members, staff training, equipment, laboratory preparation, patient preparation, data processing, data interpretation, standard file names and formats, storage location for patient data, etc…) as it is recommended by the CMAS standards [5]. They are indispensable for ensuring methodological rigor. Their implementation guarantees consistent, reliable, and reproducible outcomes across varied processes and outcomes. These protocols serve as a benchmark for quality assurance. For personnel, these documented procedures facilitate standardized training and proficiency, ensuring methodological uniformity. In inter-laboratory contexts, standardized protocols are crucial for ensuring methodological congruence, rendering results from disparate laboratories comparable, and permitting interoperability. These written protocols must be periodically reviewed and updated.

The substantial agreement, reaching at least 75% consensus on many questions within our survey, is highly encouraging as it lays a solid foundation for the subsequent Delphi process aimed at defining standards for CGA. This level of agreement reflects a consensus among a significant portion of the participating laboratories, indicating convergence on key aspects of CGA methodology and practice.

In addition to current practices, this study collated information on new devices and techniques that have emerged and have been implemented in laboratories conducting gait analysis. Furthermore, as technology evolves, there may be opportunities to incorporate innovative

tools like markerless systems [41,42], IMUs [43], or musculoskeletal modeling [44] into CGA practices. Currently, this study indicates that these innovative tools are rarely used in CGA (5% for markerless and around 10% for IMUs). Assessing the feasibility and validity of these new approaches can contribute to the continuous improvement and advancement of CGA standardization.

Limitations in our study include issues with representativeness, particularly regarding the response rates from accredited laboratories. For instance, on the CMAS website, there are 15 accredited laboratories in UK and Ireland, yet only 9 provided responses. For SOFAMEA, although 28 laboratories are reported in France on the website, only 14 provided responses. We didn't find the number of existing laboratories in other countries. This indicates potential limitations in the coverage and representation of our survey data. However, the responses from 97 gait laboratories across Europe represent a strength of this paper.

It is challenging to encompass all aspects of CGA within a single questionnaire; it is possible that some aspects are not completely covered. For example, one notable omission is the absence of questions regarding the verification of marker placement, particularly in relation to assessing the accuracy of joint axes following data collection.

Despite our efforts to ensure comprehensive data collection, certain unexpected answers emerged, notably regarding the involvement of laboratory staff in essential tasks related to data collection and analysis. Additionally, the prevalence of "I don't know" responses highlights potential gaps in knowledge regarding critical methodologies and models used in gait analysis. Table 2 provides a list of these unexpected answers. The potential reasons for these results are given below. The survey was voluntary and self-reported by each laboratory. No verification of actual laboratory activity was conducted, potentially resulting in discrepancies between reported responses and actual practices. Additionally, we only considered one response per laboratory (which may not fully capture the diversity of practices within each laboratory). For some laboratories, it could be that the clinical manager has responded and may not be aware of certain technical aspects relating to the CGA. Some responses might have been incomplete as it was not mandatory to answer every question to submit the responses. Furthermore, the questionnaire's relatively lengthy nature, consisting of 75 questions and requiring between 1 and 1.5 hours to complete, may have affected the time available for accurately responding to each question. In the end, these findings underscore the need of standards within the field of clinical gait analysis.

Table 2
List of unexpected answers.

Questions	Unexpected answers	Expected answers
[Q11]	11% are institutions other than public or private hospitals or universities	0% of other
[Q19]	Between 6% and 7% of responses showed no involvement of laboratory staff in essential laboratory tasks related to data collection, processing, analysis and interpretation	100% of involvement of the laboratory staff in these tasks
[Q24]	6% do not perform CGA on a leveled ground	100% of the laboratories perform CGA on level ground
[Q24]	26% without a minimum 7 m walking distance	Close to 100% of the laboratories perform CGA with a minimum distance of 7 m
[Q33]	between 26% and 39% of the laboratories never conducted an external quality control assessment of their main equipment	Close to 100% of the laboratories perform a quality control assessment of their main equipment
[Q62]	5% do not provide a technical report with the data collected during CGA	100% of the laboratories provide a technical report with the data collected during CGA
[Q64]	7% never report 3D kinematics of the lower limbs	100% of the laboratories report kinematics whereas kinematics is the core of CGA
[Q42]	9% didn't know the event detection method they used	100% of the laboratories know the method they used
[Q42]	30% didn't know the size of maximum fill gaps	100% of the laboratories know the method they used
[Q44]	34% didn't know how the maker trajectories are smoothed	100% of the laboratories know the method they used
[Q45]	38% didn't know how the forceplate signals are smoothed	100% of the laboratories know the method they used
[Q46]	27% didn't know how the EMG signals are filtered	100% of the laboratories know the method they used
[Q48]	13% didn't know if they use the conventional gait model	100% of the laboratories know the method they used
[Q50a]	5% didn't know the kinematics and kinetics model used	100% of the laboratories know the method they used

Based on these results, the standardization work already completed (i.e, CMAS [5]), and on the collaboration with the European national societies, the next step will be to carry out a Delphi process to define minimum standards for CGA in Europe. The Delphi method will involve gathering opinions from a panel of experts in gait analysis and related fields from various European countries. Through a series of iterative rounds of questionnaires, we aim to achieve a consensus on the best practices for CGA.

5. Conclusion

The survey conducted for this study provides new information regarding current practices and protocols employed by 97 laboratories conducting CGA in Europe. The results show a good agreement on the most used equipment in CGA, encompassing video cameras, 3D motion capture systems, force plates, and surface EMG devices. Understanding these practices, their similarities, and differences will serve as the foundation for initiating a Delphi process to support the minimal harmonization needed to establish standards for CGA. While some variability may be acceptable and necessary due to clinical diversity and national policy, excessive variation can hinder comparability and evidence-based practice. More attention should be directed towards addressing key operational aspects such as training, documentation, maintenance, and reliability evaluations.

CRediT authorship contribution statement

Fabiola Spolaor: Writing – review & editing, Conceptualization. **Marije Goudriaan:** Writing – review & editing, Project administration, Methodology, Formal analysis, Conceptualization. **Isabella Campanini:** Writing – review & editing, Conceptualization. **Brian Horsak:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Michela Cosma:** Writing – review & editing, Conceptualization. **Marjolein van der Krogt:** Writing – review & editing, Conceptualization. **Ann Hallemans:** Writing – review & editing, Conceptualization. **Catherine Huenaerts:** Writing – review & editing, Conceptualization. **Herwin Horemans:** Writing – review & editing, Conceptualization. **Colm Daly:** Writing – review & editing, Conceptualization. **David Gasq:** Writing – review & editing, Conceptualization. **Andreas Kranz:** Writing – review & editing, Conceptualization. **Florent Moissenet:** Writing – review & editing, Conceptualization. **Harald Boehm:** Writing – review & editing, Conceptualization. **Ayman Assi:** Writing – review & editing. **Maurizio Petrarca:** Writing – review & editing, Conceptualization. **Morgan Sangeux:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Anna Guiotto:** Writing – review & editing, Conceptualization. **Stéphane Armand:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Merlo:** Writing – review & editing, Conceptualization. **Zimi Sawacha:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration,

Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2024.04.014.

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