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Research Article

A DICOM-based standard for quantitative physical rehabilitation

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ABSTRACT

Physical rehabilitation (PR) is a critical medical discipline traditionally reliant on qualitative data for procedure evaluation. Recent scientific and technological advances have provided innovative instruments and methods for measuring and evaluating PR objectively through Quantitative PR (QPR). However, the lack of a standard data format creates several challenges. These include limited interoperability between devices, difficulties in maintaining patient histories, inability to perform temporal evaluations or inter-patient comparisons, barriers to data sharing, challenges in creating common evaluation scales for therapists, and limitations in statistical analysis. This article proposes a DICOM Information Object Definition (IOD) for QPR, referred to as PR-IOD, and describes its architecture. DICOM is an established standard initially created for medical imaging, but it has recently been extended to other areas of medicine. Its primary goals are to facilitate data sharing among various devices, manage associated processes, and ensure interoperability among systems and specialists by generating structured data. The implemented PR-IOD architecture has been applied to manage data by a multiple-source hand-tracking device, the Virtual Glove (VG), used for hand rehabilitation. The corresponding DICOM files have been generated, loaded, and visualized alongside a viewer dashboard specifically tailored for PR-IOD. The source code is available at [1].

1. Introduction

Physical Rehabilitation (PR) is crucial for patients who have experienced a stroke, injury, or surgery, as it helps them recover mobility, strength, dexterity, and functionality in daily life activities [2]. PR can be performed either face-to-face or remotely, at home, through telerehabilitation [3,4]. Face-to-face involves qualitative or quantitative procedures in the presence of a therapist, while remotely involves assistive technologies, mostly implementing quantitative procedures. Telerehabilitation presents unique challenges for qualitative evaluation due to the remote nature of interactions. As a result, it relies more heavily than face-to-face therapy on instruments designed to facilitate quantitative assessments. Objective numerical data enables therapists to track the rehabilitation progress, tune the appropriate treatment plan, and share analytical reports with other therapists in an interoperable environment [5], implementing Quantitative Physical Rehabilitation (QPR). In the era of precision medicine, QPR has gained consensus, allowing the creation of a patient history, comparing data from different devices, performing temporal therapy evaluation, etc. Furthermore, in quantitative rehabilitation, the patient uses supporting technologies, such as robots and virtual reality, immersed in an engaging experience that makes the therapy more acceptable and effective, yielding outcomes that are even better than direct rehabilitation [6,7]. This approach proves particularly useful for patients residing in remote areas or those with limited mobility, reducing costs [8].

On the contrary, qualitative rehabilitation, though necessary for representing patient-specific qualities, is prone to subjective and distorted interpretations, thus potentially leading to errors and information loss [9]. This is in contrast with the concept of precision medicine [10].

However, using quantitative instruments in PR requires that data be standardized to improve the results' interoperability, data comparison, and reproducibility [11,12]. Without a standard, each provider defines a proper data format, leading to issues in interoperability. This signifi-

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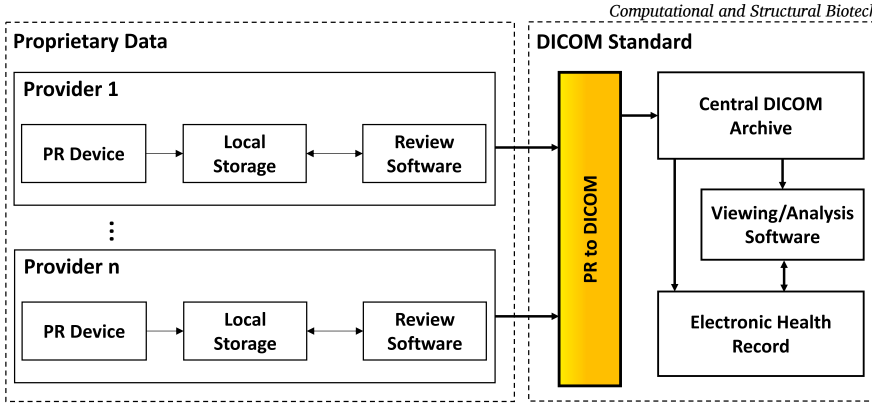

Fig. 1. PR proprietary data (left) are merged, through a PR to DICOM converter tool, into a shared DICOM-based data format (right): in this way, data can be compared and shared easier, thus improving interoperability. This Figure has been adapted from Figure 1 in [13], wherein a comparable architecture was employed for EEG data.

cantly limits the possibility of creating a patient history, comparing data from different devices or patients, performing a temporal evaluation of the therapy, making quantitative analyses based on common evaluation scales and scoring for therapists, calculating statistics, etc. The scenario under consideration is illustrated in the left panel of Fig. 1.

PR data has the complexity of medical data, particularly regarding the heterogeneity of the information, making it challenging to integrate different databases for patient information maintenance. Over the past two decades, efforts have been made to establish medical standards for data communication between various devices, including network protocols, data structures, and shared definitions [14–18]. This process has been partially performed in the context of the Electronic Medical Record (EMR) and Electronic Health Record (EHR) [19–21], though it has not yet been completed [21].

Digital Imaging and COmmunications in Medicine (DICOM) is an effective and well-affirmed standard for the representation and sharing of medical data, providing a framework that may be utilized independently or integrated with Picture Archiving and Communication Systems (PACS) [22].

QPR, whose data are collected by assistive numerical systems producing time series, is a medical domain where DICOM could significantly contribute to data standardization. To the best of our knowledge, despite DICOM's apparent compatibility with PR, its potential use in PR is still underexplored. We propose using DICOM as a standard data format in QPR, as reported on the right side of Fig. 1.

This work presents a new DICOM-based Information Object Definition (IOD) designed for QPR (PR-IOD). An IOD is an abstract template model representing and structuring information about Real-World Objects. The PR-IOD is specifically developed to support time-series data derived from tracking models of the human body or its components. To demonstrate the effectiveness of DICOM in representing QPR data, a scenario of its application to data collected by an assistive, multi-modal hand-tracking device named Virtual Glove (VG) [23] is presented and discussed, along with its implementation as a proof of concept. The remainder of this paper is organized as follows: Section 2 outlines related work; Section 3 describes the DICOM architecture, provides an overview of the physical rehabilitation devices and associated data, and discusses the integration of both in the PR-IOD; Section 4 illustrates the results and discussion presenting a PR-IOD use case involving the VG; Section 5 summarizes the conclusions and proposes directions for future research; Finally, Table 5 provides a comprehensive list of acronyms used throughout the paper.

2. Related work

QPR uses various data formats to capture and manage information. Commonly utilized file formats include JSON [24–27], XML [28], TXT [29], CSV [27,30,31], and C3D [31,32]. While these formats vary in maturity and adoption across clinical and research contexts, each presents unique challenges. General-purpose formats such as JSON, XML, TXT, and CSV are relatively straightforward to implement and offer flexibility in defining fields. However, this flexibility often necessitates manual agreements between collaborators on field definitions, limiting their suitability for standardized clinical use. These formats also lack domain-specific constructs such as standardized metadata fields, patient identifiers, or detailed device information, which are critical for clinical interoperability. C3D, a widely adopted format for motion analysis and time-series data, provides additional features, including metadata for measurement units, data point labels, and patient-specific information (e.g., diagnoses and evaluation protocols). However, the effective use of C3D is often hindered by its reliance on ad hoc agreements for data definitions, limiting its interoperability across institutions [33]. In contrast, the DICOM standard offers a robust and comprehensive solution to these challenges. Initially defined for medical imaging, DICOM has expanded over the years to encompass other medical domains, including time-series data such as ECG, EEG, and EMG [34]. This expansion has been supported by standardization efforts that address the needs of diverse clinical applications [11,13,35–40]. One of DICOM's key strengths lies in its hierarchical information model, which systematically organizes metadata related to patients, specimens, equipment, and studies [39]. This structured approach ensures standardized identification, traceability, and retrieval of data, addressing the meta-data and interoperability limitations of JSON, TXT, XML, and C3D. Additionally, DICOM's compatibility with PACS facilitates efficient data management, secure sharing, and long-term archiving, further enhancing its utility in healthcare contexts [22].

Table 1
Comparison of various file formats for managing QPR data.

	JSON/XML/TXT/CSV	C3D	DICOM
Interoperability	Low	Medium	High
Standard Compliance	None	Limited	High
Integration with PACS	Low	Low	High
Time-Series Handling	Medium	Robust	Robust
Vendor Independence	Partial	High	High
Metadata Handling	Limited	Moderate	High

Table 1 highlights DICOM's advantages over alternative file formats for managing rehabilitation data. A new IOD, specifically designed for QPR and called PR-IOD, is proposed to overcome the limitations of existing approaches. This PR-IOD leverages the Waveform Module and incorporates private elements to address the specific requirements of QPR. These customizations align with core DICOM constructs, such as

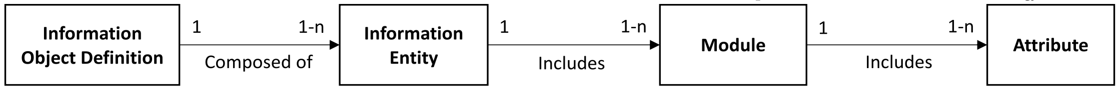

Fig. 2. Information Object Definition Model composition.

patient and study metadata and equipment details, while enabling precise time-series data modeling. This includes multi-channel signals and kinematic parameters from motion analysis.

3. The DICOM architecture

The DICOM standard represents and connects real-world data using the Object Oriented Paradigm (OOP). Specifically, it employs the notion of **attributes** to collect and define physical world data, **methods** to delineate the procedures applied to attributes, and **classes** to integrate attributes and methods. Finally, **objects** are used to create instances of **classes** [18].

3.1. Core information model and methods

DICOM represents real-world entities, such as **Patient** or **Image**, as a specific Information Entity (IE) contained in the IOD. Any IOD can be Normalized if composed by a single IE, or Composite if consisting of a combination of IEs (Fig. 2) [41].

The IE amalgamates attributes associated with the real-world entity it represents. The correlated attributes are then organized into modules, and the last are contained by the IE (Fig. 2). Attributes are defined by a tag name, a description, and a type (the type can be: required, optional, or conditionally required).

An IOD is an object-oriented abstract data model that specifies information about a class of real-world objects with similar features and is used to represent the relationship between the IEs it contains.

An example is represented by the “General Electrocardiogram (ECG)” IOD, which specifies biosignals collected with an ECG [42].

With this structure, DICOM provides a comprehensive framework for organizing IEs and interconnecting them through constraints (Fig. 3), in which every Composite IOD inherits entities and relationships from the framework.

An example of a composite IOD is the “Magnetic Resonance Image” IOD, which encompasses data regarding the patient, the study conducted, and the image acquired by a magnetic resonance imaging system [43]. This IOD includes all IEs from the patient block to the series block, which ultimately culminates in the inclusion of the Image IE.

In DICOM, the IOD has also associated operational services and methods called DIcom Message Service Element (DIMSE) [45]. These services can be inherited by IODs designed for specific applications, as well as the used structured classes.

The Sevice Object Pair (SOP) Class is the outcome of DICOM standard [18]. It is defined as the union of IODs and DIMSE services (Fig. 4). This concept works as a contract, since it is what is exchanged among two Application Entitys (AEs).

4. DICOM IOD design for physical rehabilitation

This section provides an overview of physical rehabilitation devices with the associated data. Subsequently, the structure and pipeline of the PR-IOD are illustrated.

4.1. Equipment

Various injuries require different PR procedures [47] involving specific devices and technologies to support QPR. Devices supporting QPR may include [48]:

- Inertial Measurement Units (IMU)
- Pressure Sensors
- Electromyography (EMG) Sensors
- Camera-based Systems
- InfraRed (IR)-based Systems.

An IMU is a device that uses accelerometers, gyroscopes, magnetometers, and (sometimes) a barometer, all in the same device, to provide information regarding position, orientation, velocity, acceleration, as well as any other parameter derived from them [49].

Pressure sensors measure the exerting pressure applied to the sensor [50]. An example of this system is the Force Sensitive Resistor (FSR), which changes its resistive value depending on how much it is pressed.

The EMG systems record the electrical signals of muscle activity during movements. Signal recording involves the utilization of disposable concentric needle electrodes inserted within the muscle [51].

Camera-based systems encompass marker-based and markerless methodologies [52]. Marker-based systems require the application of physical markers for the acquisition of kinematic data. In contrast, markerless systems rely on video cameras and auxiliary devices to capture the body’s motion. They employ computer vision techniques and/or artificial intelligence methods to extract kinematic data. This allows for generating a computational model of the body or its components.

IR-based systems include the usage of commercial devices, such as the Leap Motion Controller (LMC) [53] and Microsoft Kinect [54], whose behavior is very similar to camera-based markerless solutions. In particular, LMC is a compact device that uses stereo vision to provide a 4D representation of the movement of a human hand divided into 25 joints. The Kinect is an RGB-D sensor designed for the real-time tracking and recognition of the human body. This system provides diverse data types, including depth, RGB, and IR data. The above systems can be used singularly as atomic tools [55–57], or can be mutually integrated into multiple-source systems [23,58,61].

These systems can be effectively integrated with Virtual Reality (VR) to improve patient engagement [59]. Data generated by these devices predominantly takes the form of time series, providing information regarding spatial position, angles, velocity, acceleration, etc.

4.2. Task-based numerical tracking and data generation

QPR is founded on the patient’s deep engagement with assistive devices and interaction with the therapist. The assistive device allows the patient to execute a specifically designed rehabilitation task while performing numerical data acquisition, processing, reconstruction, and storage. The therapist is responsible for defining the task and setting its difficulty level based on the patient’s infirmity and residual capabilities. With the task definition, some metadata are generated, including the task type, difficulty level, recommended repetitions, repetition duration, etc. Upon task assignment and setting, the patient proceeds to its execution by completing all the recommended repetitions. During the task execution, time series are generated, consisting of the raw data (temporal data directly measured by the sensors), a dynamic model of the tracked part of the body reconstructed by using the raw data, and annotations of data referred to specific time-instants of the task. VR-based information belonging to the repetition is also created, such as the task score, time used to complete the task, etc. Fig. 5 shows the actors involved in the QPR pipeline and the data generated after the execution of a rehabilitation task.

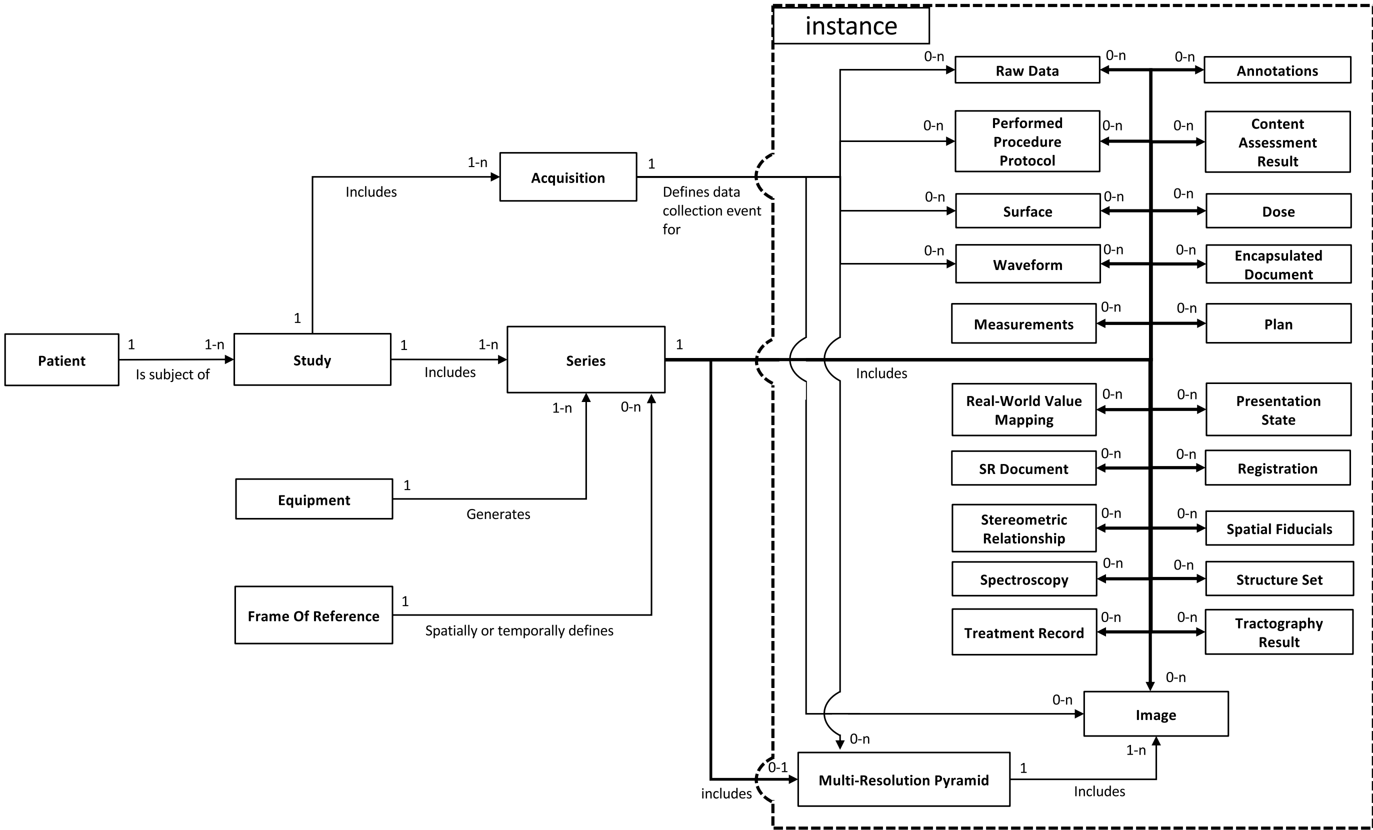

Fig. 3. DICOM conceptual framework where relationships and constraints among IEs are reported [44].

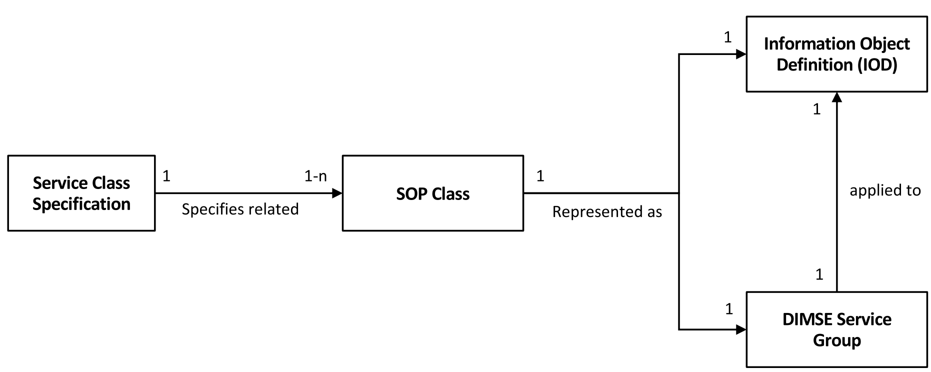

Fig. 4. The DICOM Information Model delineates the interconnections among the main components of the standard [46].

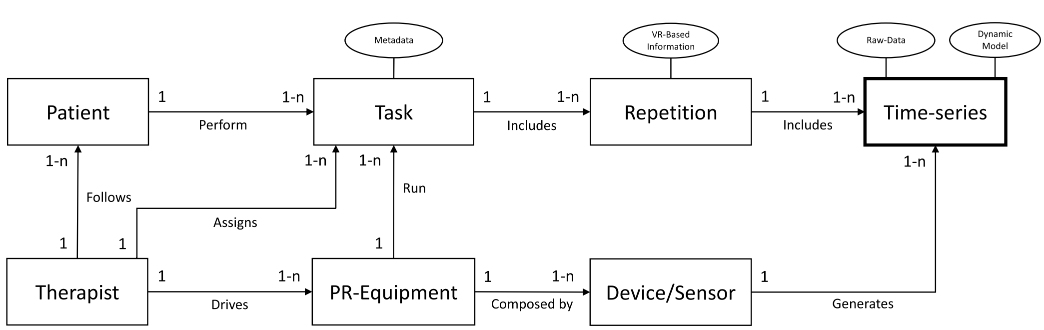

Fig. 5. Actors involved in the QPR Pipeline and data generation.

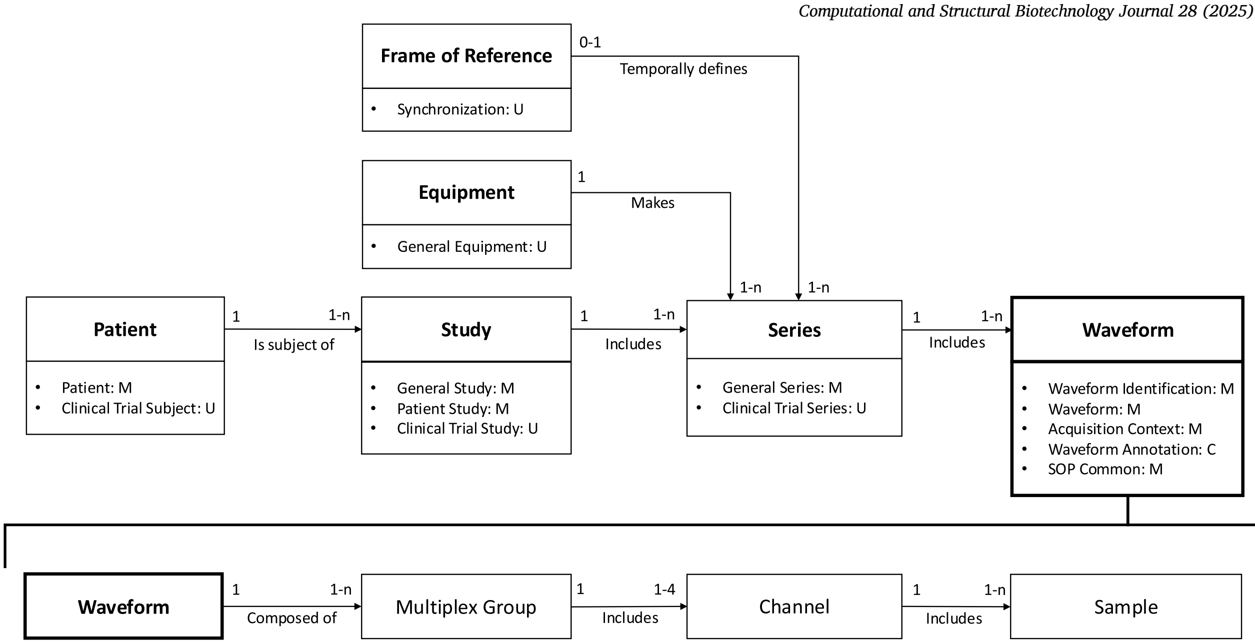

Fig. 6. Relationship between IEs involved in the PR-IOD Model; every IE is composed of modules. Every module specifies its usage, which can be Mandatory (M), User Optional (U), or Conditionally Required (C). The Waveform IE has been further divided to show its composition (structure adapted from [60]).

4.3. PR-IOD structure

The IOD defined for QPR can be directly derived from the general composite model (Fig. 3), which is a structure used in various clinical contexts to manage time series. The resulting architecture is reported in Fig. 6. In this way, adherence to DICOM is maintained. A short description of the involved IEs, related modules, and attributes is furnished in what follows.

4.3.1. Patient IE

The Patient block contains attributes describing its general characteristics (Patient Module). This IE also contains attributes in the Clinical Trial Subject Module that describe the Patient as a participant in a clinical trial or research. Thus, this IE perfectly includes the patient's attributes in QPR.

4.3.2. Equipment IE

The device the patient uses to generate the Series is the Equipment IE. The Equipment specifies only the device type employed (General Equipment Module).

A specific Equipment can create many series; each Series is associated with one Equipment. Finally, this IE contains the attributes of the Equipment in QPR.

4.3.3. Study IE

Within this IE, the attributes delineate the specifics of a medical examination (General Study Module), as in Fig. 6. This block also includes information on the patient's status, residual infirmities, and specific attributes regarding the therapist and the clinic involved (Patient Study). Lastly, it contains the Attributes to identify a Study in the context of a potential clinical trial or research (Clinical Trial Study).

A Patient can have more than one Study. However, each Study is exclusively associated with one Patient. In the context of QPR, the Study represents the specific task assigned to the patient. Consequently, various attributes related to the task, such as its type, level of difficulty, number of repetitions, duration, and other relevant parameters, are documented and maintained within this IE. However, these metadata are not incorporated within the General Study Module. Instead, they are implemented as private data elements, ensuring flexibility without compromising the generality (as shown in Table 2).

Table 2
New Private Data Elements in the Study IE pertain to the task that the patient has to carry on.

Private Data Elements			
Name	Description	Type	Value Representation
Difficulty	Difficulty of the task	Optional	DS (Decimal String)
Duration	Total duration of repetition	Conditional	DS (Decimal String)
Repetitions	Number of repetitions	Required	DT (Date Time)

4.3.4. Series IE

The Series IE provides detailed information regarding the instance Waveform (Fig. 6). This includes attributes such as the specific date and time of the series' creation, details about the type of examination conducted, and the equipment employed (General Series Module) [41]. Additionally, this IE contains attributes related to clinical trials (Clinical Trial Series). In the context of QPR, the series delineates different repetitions of a given task, where each new series corresponds to a new execution. Beyond the standard attributes, additional metadata are incorporated to capture task-specific details, such as the time required to complete the current repetition and the score achieved, when applicable (as shown in Table 3). It is important to note that these metadata elements are not defined within the standard and must be introduced as new private elements. While a Study may comprise multiple Series, each Series is uniquely associated with a single Study.

Table 3
New Private Data Elements in the Series IE specific for each task repetition.

Private Data Elements			
Name	Description	Type	Value Representation
Final Time	Absolute final time	Optional	DT (Date Time)
Score	Score attained	Optional	DS (Decimal String)

4.3.5. Frame of reference IE

The Frame of Reference IE is used to synchronize different instances of a series or different data sources collected simultaneously by different sensors.

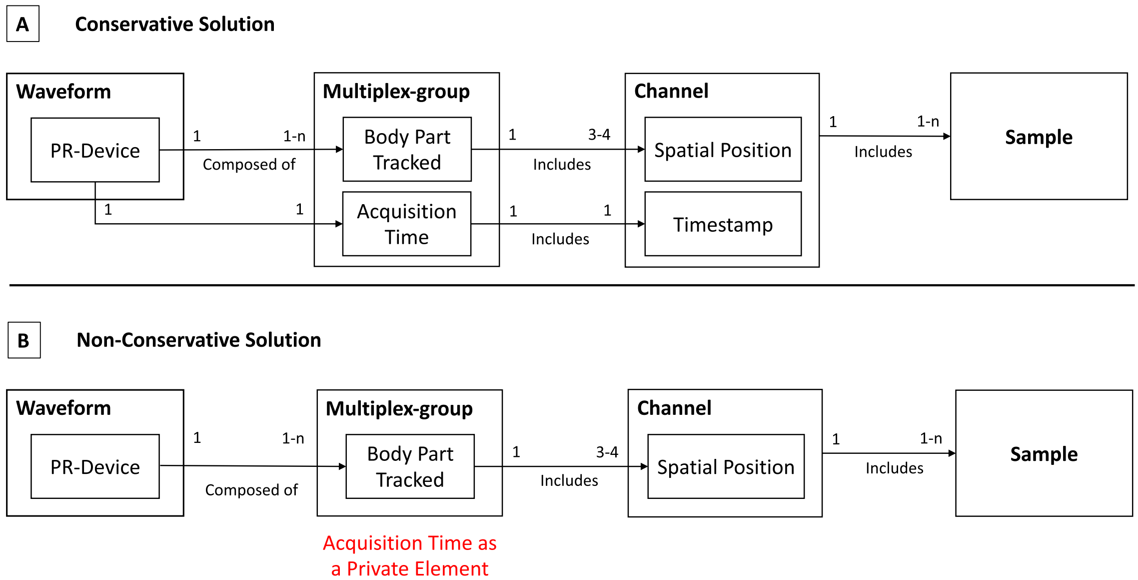

Fig. 7. QPR Waveform decomposition including the acquisition time-series for a QPR-Device having a variable sampling rate; the Conservative Solution (A) involves using an additional Multiplex-group composed of one channel; the Non-Conservative Solution (B) designates a private element for its storage.

This IE can be associated with several Series, but each can be related to just one Frame of Reference. Since QPR may employ several sensors simultaneously (Fig. 6), the proposed IE adequately meets QPR criteria.

4.3.6. *Waveform IE*

The Waveform IE is fundamental to the storage of multichannel time-series data; however, additional adaptations are required to accommodate QPR. In detail, the Waveform Module is represented as a composition of several Multiplex-Group (Fig. 6). A Multiplex-Group has the potential to manage several Channels. The time series in each channel is stored using a predetermined and constant number of samples. In QPR, every time series a sensor produces finds its association within a Waveform IE. This association signifies that the sensor data, encompassing each tracked section of the body, is mapped within a Multiplex-Group. These mappings are further defined in channels by spatial coordinates or angles, providing precise spatial orientation information for each section. Consequently, the mapping process results in the creation of a dedicated time series for each channel. The number of Multiplex-groups included in the Waveform IE is unconstrained (Fig. 6). Each Multiplex-Group is supported by one to four channels. This range accommodates basic positional data and rotational information encoded as quaternions, which require four distinct channels to represent three-dimensional orientation accurately. Moreover, DICOM requires that all channels be digitized synchronously at the same sampling frequency in a multiplex-group. However, this approach does not align with rehabilitation data sources, where data from different sources can be frequently sampled at different sampling frequencies. Accordingly, in PR-IOD, the sampling frequency might be unconstrained. To this end, a new data element must be introduced in which each time series sample is associated with its timestamp. Unfortunately, the DICOM standard does not provide such a field for QPR. To address this lack, two solutions, one conservative and one non-conservative, are proposed (Fig. 7). The conservative solution implies that a new Multiplex-Group with a single channel is created (Fig. 7A). The non-conservative approach involves creating a new private element where the acquisition time for the entire waveform is specified (Fig. 7B). Table 4 shows the specifications of the last solution.

In addition, DICOM mandates that each Channel incorporate several required attributes, including Channel Source, Channel Sensitivity, Skew, and Filter Characteristics. Moreover, this IE includes attributes defined in the Waveform Annotation Module, which allows the collection of annotations during acquisition. It is also possible to describe the conditions present during data acquisition that can alter the measurement of QPR devices (Acquisition Context Module). This IE also contains Attributes required for the correct operation and identification of the associated SOP instance (SOP Common Module). Finally, some related Waveform attributes are used to delineate the Waveform as a separate IE (Waveform Identification Module).

Table 4
New Private Data Element in the Waveform Module pertains to the sampling time if the system employed does not perform frequency acquisition at a fixed time.

Private Data Element			
Name	Description	Type	Value Representation
Acquisition Time	Time-Series specifying the acquisition time for each sample	Conditional	OW (Other Word)

5. Results and discussion

This section presents how data from a touchless hand rehabilitation device, the VG [23,61], can be integrated into the DICOM format using the PR-IOD. This follows the acquisition-hand model-DICOM pipeline shown in Fig. 8.

5.1. *PR-IOD for the QPR of the hand: an example*

The VG is a touchless hand-tracking system consisting of two synchronous LMCs mounted in an orthogonal arrangement. The LMC-based solution of the VG reduces occlusions, thus enhancing the precision of hand-tracking in the rehabilitation process in an online telerehabilitation context [25,58,62]. The hand model of the VG is composed of frames, each representing a temporal snapshot of the hand's position and movement. These frames capture detailed data about the detected hand, including the coordinates of 25 joints and their corresponding timestamps. Each joint reflects either the connection between two bones or the endpoint of a bone (such as a fingertip) and provides precise three-dimensional coordinates (x, y, z), along with calculations for velocity

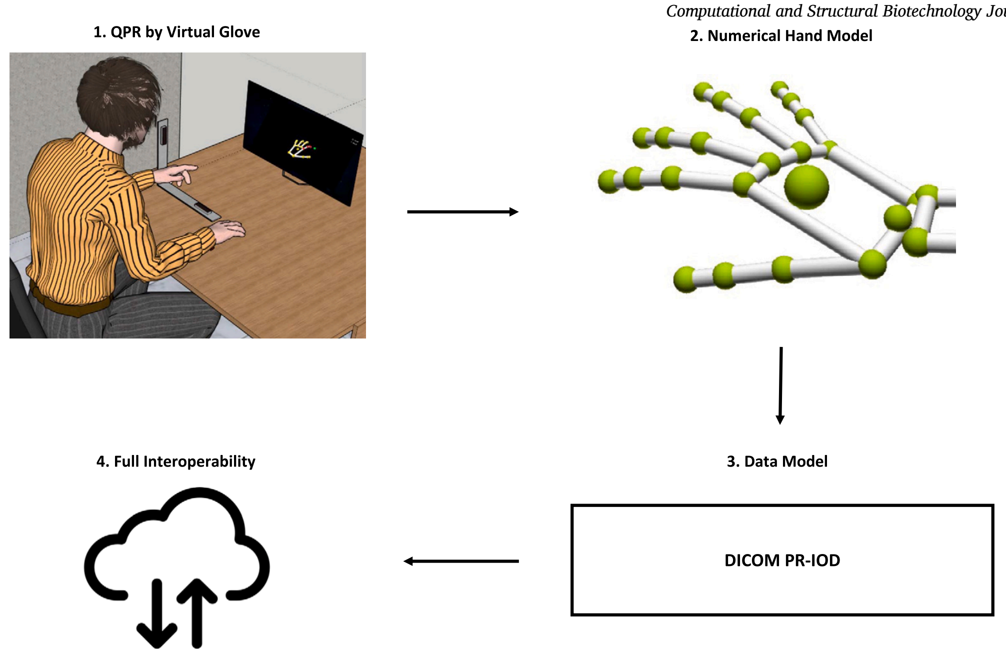

Fig. 8. QPR of the hand: from data acquisition to PR-IOD definition, passing through the hand model construction.

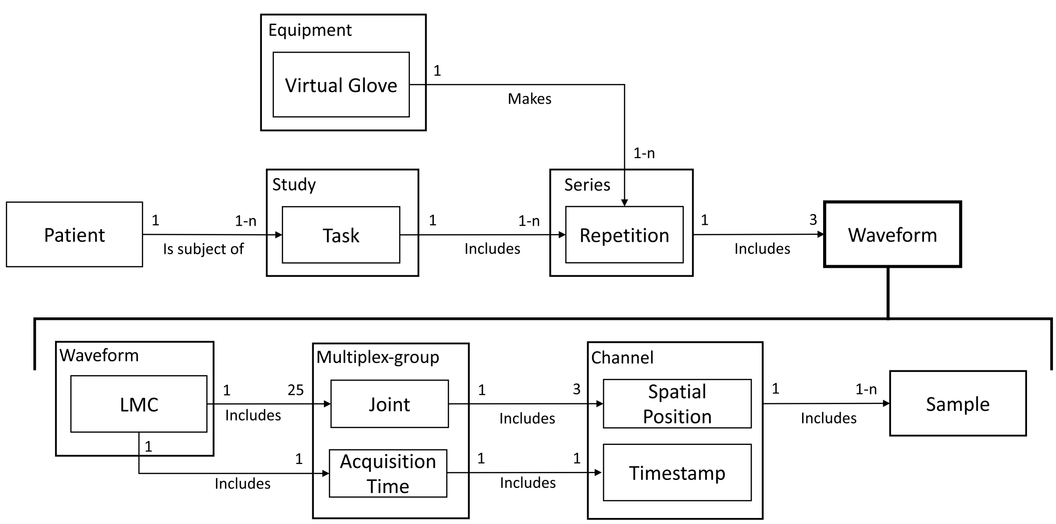

Fig. 9. Overall structure of data in VG-Patient-Task within the PR-IOD: the used IEs are reported (being the Frame of reference IE not used in the VG-Patient-Task assembly, it has not been reported).

and acceleration. Beyond joint-specific data, the system also tracks additional hand-related metrics, such as palm position and velocity. Moreover, the VG has been calibrated to operate within a unified reference system [23]. The integration algorithm for the two LMCs uses a binary switching method, selecting data from the LMC that has the best view of the palm [23].

Within the VG framework, the therapist can assign specific rehabilitation tasks to the patient, set execution parameters, and conduct quantitative analyses from the resulting collected data. The data managed within the rehabilitation includes the following categories:

- **Patient Information, including Anamnestic Data:** This provides patient details and information about the disease, residual capabilities, suggested treatment, and the required QPR procedure.
- **Therapist Metadata:** This covers metadata associated with the therapist, including qualifications and specialty.
- **Task Metadata:** It includes details about the assigned rehabilitation task, such as the type of exercise, duration, difficulty level, instructions, etc.
- **VG Metadata:** It includes general information about the VG device, such as the serial number, the producer, precision, etc.
- **VG-Related Task Data:** It includes all the time series generated by the VG during the executions of rehabilitation tasks.

The structured details of the data in PR-IOD for VG are reported in Fig. 9.

Patient information is conveyed through the Patient IE, specifically within the Patient Module. Anamnestic data are included in the Patient Study Module, located in the Study IE. Therapist details are stored in the General Study Module of the Study IE, which also accommodates the therapist-assigned Task metadata. Notably, specific task information (such as task difficulty, duration, and similar parameters) can only be incorporated via the non-conservative solution, relying on private elements within the General Study Module. Information regarding the structure of the QPR device, the VG, is contained within the Equipment IE. Task repetition. Data are incorporated as private elements within each rehabilitation task. A new Series IE represents each iteration of the task, and associated metadata (e.g., final score, total execution time) are likewise embedded in this IE as private elements. All time series generated by an LMC sensor during a single task repetition are stored within the Waveform IE. A new Waveform IE is created for each distinct type of LMC data. The VG output can be categorized into three data types: those derived from the horizontal LMC, those derived from the vertical LMC, and those obtained through a fusion of both sources [23]. Because data from each LMC represent raw output, the usable VG results arise through the integrated processing (fusion) of both devices' data. The LMC reconstructs a numerical model of the hand comprising 25 joints. Consequently, each joint is assigned its own Multiplex-Group, and each spatial coordinate is mapped to a distinct channel within that group. The time series is then specified via channel samples. As the LMC does not operate at a fixed sampling frequency, each frame is assigned a timestamp through a dedicated, single-channel Multiplex-Group. The number of samples for each Multiplex-Group and each channel is thus identical. In Fig. 9, the Frame of Reference is not depicted because its management is handled by the LMC driver, thereby ensuring that the two LMC devices share the same temporal reference.

5.2. Proof of concept

To demonstrate the application of PR-IOD with VG, we leveraged data from a repetition of a specific VR-based hand movement exercise [25]. This data was collected and initially exported into the following CSV files:

- Patient File: This contains patient-specific data
- Exercise File: This contains details regarding the performed exercise, including metadata about its parameters, final score, and duration
- Therapist File: This contains data of the therapist involved in the patient's care
- Time Series Data File: This contains the spatial-temporal trajectories of the hand joints, for the entire duration of the exercise (the stick model of the hand).

We first converted the above data into DICOM using the PyDICOM library [63]. Pydicom is a popular tool for creating and managing DICOM files. Our study focused on acquiring time-series data for a hand model, capturing the positional information of 25 joints at each time instant. Each joint was represented across three channels x, y, and z coordinates. To process this multidimensional data effectively, we utilized the Waveform Module. In particular, we allowed the converter to manage a DICOM file with 25 multiplex groups, each with three channels. To take into account the variable frame rate of the LMC, we opted for the conservative solution (as discussed in section 4.3.6). Other information regarding the patient, the therapist, and the exercise was included in the precisely defined DICOM fields, most of which are already available in DICOM. Finally, we have implemented a DICOM Viewer, consisting of a PyQT [64] program. The program opens the resulting DICOM file, views its data, performs data analysis, and allows data comparisons. Some sample screenshots of the implemented Viewer are reported in Fig. 10. As can be observed, the Viewer can display, for each selected joint, the original data and spatial trajectories and calculate and display velocity and acceleration. Besides, the Viewer uses an interactive scatter plot to display the temporal movements (at actual, slow, or accelerated speed) of the hand model as a whole or for some selected finger. The resulting files, both containing the developed software and the DICOM data, are accessible on GitHub [1].

6. Conclusion

In this work, we have addressed the need for a standard data format in QPR based on the DICOM standard. The proposed PR-IOD stores time series using the Waveform IE, already available in DICOM. This maintains DICOM's structure while introducing new features for QPR.

In this way, we ensured that the defined PR-IOD is fully compatible with the DICOM, from which it derives all the advantages regarding interoperability. A proof of concept of the model has been presented for the VG assistive system for the QPR of the hand. Our primary goal was to demonstrate the effectiveness of using the DICOM format for QPR without necessitating significant modifications. The DICOM compatibility of QPR allows the promising avenue for integrating PR data into the broader spectrum of other medical fields, thereby allowing multimodality, improving interoperability, and the inclusion of QPR in broader clinical and research settings in a vendor-independent data access modality.

Moreover, integrating DICOM with QPR time-series data can significantly streamline patient care by consolidating multiple studies into a standardized format. While the PR-IOD framework provides a promising foundation for this integration, some limitations must be acknowledged. Adapting DICOM for QPR involves introducing private data elements to accommodate variable sampling rates and rehabilitation-specific metadata, thereby reducing overall interoperability. The PR-IOD has been validated solely with the VG system, creating the tool for converting device-generated data into DICOM data specific to VG. Nevertheless, extending the converter to support additional QPR devices would require minimal modifications, suggesting that the framework could be readily adapted to a broader range of rehabilitation technologies. This work emphasized that utilizing well-established standards and formats is generally more advantageous than developing novel ones. While we provided the seminal idea, a specific standard organization demands the final implementation of a complete and entirely consistent PR-IOD, which extends well beyond this paper. Once this novel IOD is established within the official DICOM framework, ensuring compliance with all required specifications, the subsequent phase will involve developing software to assess the validity of DICOM in QPR [65].

Table 5
List of Acronyms.

Acronym	Definition
AE	Application Entity
DICOM	Digital Imaging and Communications in Medicine
DIMSE	DIcom Message Service Element
ECG	Electrocardiogram
EEG	Electroencephalogram
EHR	Electronic Health Record
EMG	Electromyography
EMR	Electronic Medical Record
FSR	Force Sensitive Resistor
IE	Information Entity
IMU	Inertial Measurement Unit
IOD	Information Object Definition
IR	InfraRed
LMC	Leap Motion Controller
OOP	Object Oriented Paradigm
PACS	Picture Archiving and Communication System
PR	Physical Rehabilitation
PR-IOD	Physical Rehabilitation Information Object Definition
QPR	Quantitative Physical Rehabilitation
SOP	Service Object Pair
VG	Virtual Glove
VR	Virtual Reality

CRediT authorship contribution statement

Alessandro Di Matteo: Writing – original draft, Methodology, Investigation. **Daniele Lozzi:** Writing – review & editing, Visualization.

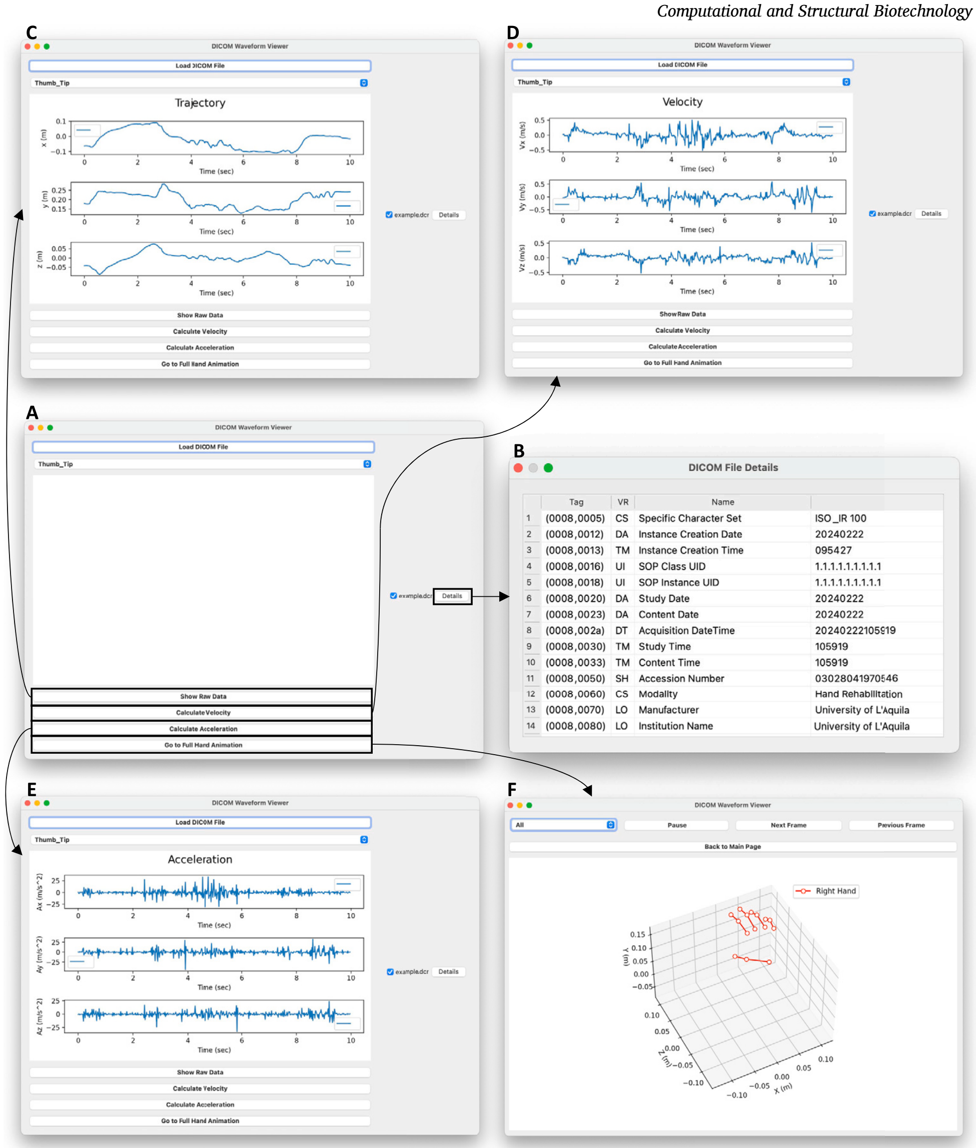

Fig. 10. Viewer Interface for feature calculation and display: (A) Main Window for navigation through data and functions; (B) DICOM Field Window to show all fields, including TAG, VR, Name, and Value; (C) Trajectory feature components of a selected finger joint; (D) Velocity feature components calculated from the trajectory of the selected finger joint; (E) Acceleration feature components computed from the corresponding velocity; (F) Interactive Plot Window showing dynamic scatter plot animations of the whole hand or separated by fingers.

Filippo Mignosi: Writing – review & editing, Visualization. **Matteo Polsinelli:** Writing – review & editing, Visualization. **Giuseppe Placidi:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, 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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