A Linked Data Visualiser for Finite Element Biosimulations

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Biosimulation models are used to understand the multiple or different causative factors that cause impairment in human organs. Finite Element Method (FEM) provide a mathematical framework to simulate dynamic biological systems, with applications ranging from human ear, cardiovascular, to neurovascular research. Finite Element (FE) Biosimulation experiments produce huge amounts of numerical data. Visualising and analysing this huge numerical biosimulation data is a strenuous task. In this paper, we present a Linked Data Visualiser–called SIFEM Visualiser–to help domain-experts (experts in the field of ear mechanics) and clinical practitioners (otorhinolaryngologists) to Visualise, analyse and compare biosimulation results from heterogeneous, complex, and high volume numerical data. The SIFEM visualiser builds on conceptualising different aspects of biosimulations. In addition to the visualiser, we also propose how biosimulation numerical data can be conceptualised, such that it sustains the visualisation of large numerical data. The SIFEM Visualiser aims to help domain scientists and clinical practitioners exploring and analysing Finite Element (FE) numerical data and simulation results obtained from different aspects of inner ear (Cochlear) model — such as biological, geometrical, mathematical, and physical models. We validate the SIFEM Visualiser in both dimensions of qualitative and quantitative evaluation.

Keywords: Biosimulations; visualisation; linked data.

1. Introduction

Mathematical models have been recently introduced into the study of human organ physiology and pathology, giving insight into the system's behavior and attributes that would have been impossible to have with human in-vivo studies. The mathematical models, specifically biosimulation models play a fundamental role in the scientific practice with regard to the understanding of biological systems [1]. To simulate dynamic biological systems, Finite Element Method (FEM) provide

a mathematical and computational framework. The applications of FEM in terms of simulating biological systems range from human ear, cardiovascular, to neurovascular research. The Finite Element (FE) biosimulation experiments are performed on biosimulation models, where these models span across multiple, complex and semantically incompatible domains, such as biological models, geometrical structures and mathematical-physical models.

FE biosimulation models are complex and sophisticated systems. Additionally, visualising and analysing results of biosimulation experiments performed on these FE models can grow unmanageable, due to volume, heterogeneity, and complexity of numerical data. A biosimulation model is a system of mathematical equations encoded in a computational language, representing different and often heterogeneous mathematical parameters. There are various tasks involved in performing a biosimulation experiment on a biosimulation model, such as defining geometry of the biological system, creating a mathematical mesh, defining input numerical parameters, solver usage, visualisation and result/output interpretation. Most of these tasks are usually performed in isolated environment, hence, a biosimulation experiment takes many hours. Among these tasks, visualisation, analysis, and interpretation of biosimulation experimental results is a challenging task for the domain-experts.

In this paper, we propose a Linked Data Visualiser that shows biosimulation results along multiple dimensions. The aim is to combine, link and visualise different biosimulations data (such as biological, geometrical, mathematical, physical) for inner ear (cochlea) mechanics. The main contributions of this paper are: (i) Conceptualise biosimulation concepts to sustain visualisation of large biosimulation numerical data; (ii) visualise and analyse high volume, heterogeneous, and complex numerical data; and (iii) validating SIFEM Visualiser on a real-life use case including experimental datasets, terminologies, and models provided by clinical organizations. Although, the proposed platform is validated against an inner ear use case, we argue that the platform can be tailored with minor adjustments to other FE biosimulation domains.

Section 2 describes the motivational scenario behind our work; Section 3 gives an insight into the conceptual model used by the SIFEM visualiser; Section 4 details the SIFEM Visualiser; Section 5 highlights the validation of SIFEM Visualiser across both dimensions of quantitative and qualitative evaluations; Section 6 describes related work preceding conclusions and future work given in Sec. 7.

2. Motivation Scenario

Our work is motivated by the need of clinical organizations and labs conducting biosimulation experiments to understand the exact pathophysiological consequences and risk factors of hearing impairment in humans. Our work is conducted in context of the SIFEM EU project[a], which aims at developing an open-source linked data platform for Finite Element multi-scale modeling and biosimulation of the

[a] http://www.sifem-project.eu/

sensorineural hearing loss. There are three major parts to the ear, with distinct functions; The outer ear collects sound waves and funnels them towards the middle ear. The middle ear ossicular chain oscillates in response to the airborne pressure waves, generating pressure waves in the inner ear fluid chambers. The inner ear turns pressure waves into electrical signals that our brain can understand. The hearing impairments, which could lead to hearing loss, are mainly caused by cochlear and cochlear nerve pathology and are classified as sensorineural hearing loss [2].

The inner ear is inaccessible during life, which leads to unique difficulties in studying its normal function and pathology. Thus, biopsy, surgical excision and other conventional techniques of pathological studies are not feasible, without further impairing function [2]. Mathematical modeling is therefore particularly attractive as a tool in researching the cochlea and its pathology. Mathematical models were introduced into the study of cochlear pathology and physiology, providing a useful tool in order to observe the system's behavior, which was impossible in previous human in-vivo studies [3]. The Finite Elements Method (FEM) — a mathematical framework — is assisting researchers in studying the structure-function relationship in normal and pathological cochlear. Figure 1 shows a set of FE parameters, values and their datatypes required to model the cochlea (inner ear). Usually, hundreds of such parameters and billions of instances (i.e. values) are required to construct a full-fledged cochlea (inner ear) model. Once a set of parameters and values are collected a numerical solver performs the finite element calculations with simulation results

Parameter Type	Parameter Value	Datatype
MESH DIVISIONS	4.0 4.0 3.0	DIV_L, DIV_W, DIV_H
GEOMETRY	0.035 0.001 0.001 3.0E-4 5.0E-5	(DOUBLE)LENGTH (DOUBLE)HEIGHT (DOUBLE)WIDTH
LOAD FREQUENCY	50 1.0	(DOUBLE)FREQUENCY (DOUBLE)VALUE
MATERIAL PROPERTY	1000 1500.0	DENSITY_RHO, (DOUBLE)SPEED_OF_SOUND
YOUNG MODULUS FUNCTION	0.000000 14101716.454877	(DOUBLE)X_AXIS, (DOUBLE)Y_AXIS
EXTERNAL LOAD FREQUENCY	1.000000e-03 1 1 1 0 1 1 1 1 0.000000e+00	DISPLACEMNT_X, DISPLACEMNT_Y, DISPLACEMNT_Z
HEADING CARD	6060 1 1 1 1 0	IFORM, ISOLVER
NODAL POINT DATA	1 0 0 90 0.000000 1.00e-002 2 1 1000.000	FREQUENCY

Fig. 1. Finite Element numerical parameters, terminologies and format.

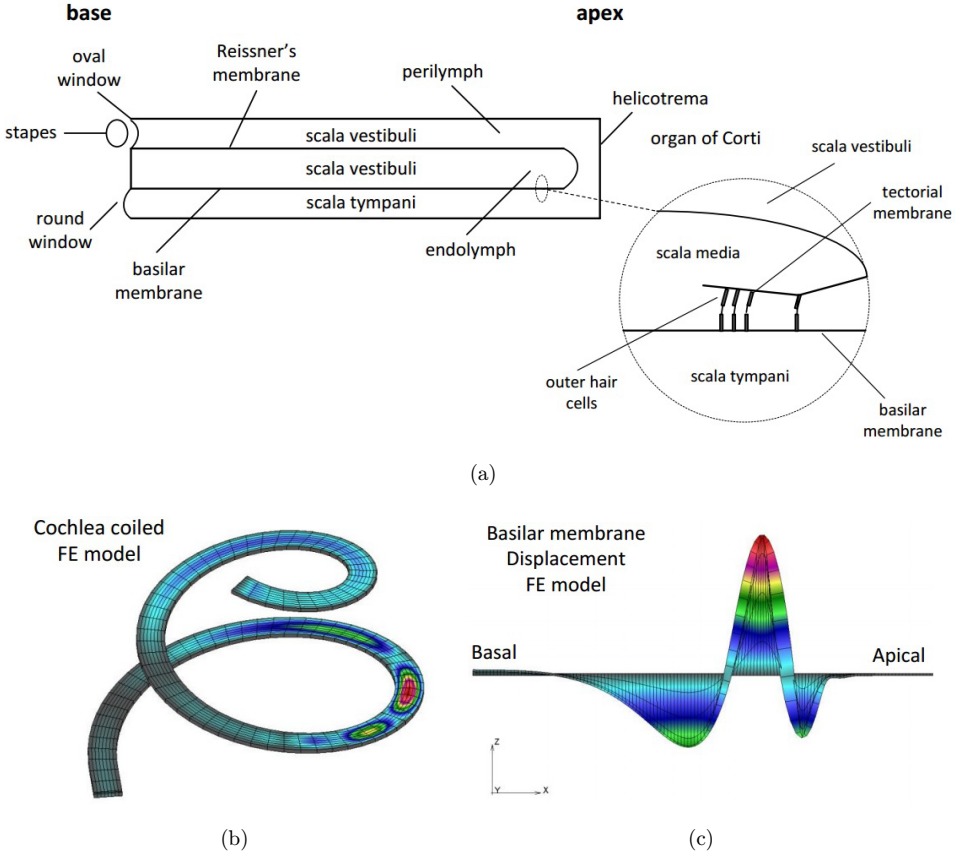


Fig. 2. Schematic representation of the human cochlea.

displayed in graphical format. Figure 2 shows schematic representation of the human cochlea with its main anatomical references, along with examples of simulation outputs from a numerical solver — called PAK Solver [4] — developed by the SIFEM consortium.

The proposed SIFEM Visualiser addresses following challenges in integrating, interpreting and visualising numerical parameters along with simulation results: (i) resolve different data formats by transforming them into standard RDF format. For instance, all the eight (8) parameters and their values shown in Fig. 1 are taken from separate experimental data files stored in different formats (e.g. .dat, unv, .pak, etcetera); (ii) providing links across input parameters/values and simulations results in-order to reuse relevant data analysis in future experiments; and (iii) Visualisation and data analysis over FE simulation results.

The cochlea (inner ear) represents a complex bio-mechanical device and a complete understanding of its behavior is still an open research problem. To the best of our knowledge, the proposed SIFEM Visualiser is a first attempt to bring together

numerical parameters, models, terminologies, storage, querying using Linked Data technologies to leverage visualisation and analysis over finite element biosimulations.

3. Conceptualising SIFEM Visualiser

This section describes the conceptualisation of FE Biosimulation experiments data which spans multiple interrelated domains producing heterogeneous data models, such as biological, geometrical, mathematical and physical models. The purpose of conceptualisation is to standardise and integrate the complex and heterogeneous data to form a basis for visual analysis on this data in an integrated manner. SIFEM Visualiser is based on the FE Biosimulation experimental data represented using the SIFEM conceptual model.

3.1. *SIFEM conceptual model dimensions*

The SIFEM conceptual model depends on the representation of multiple, interrelated domains. The different dimensions of the conceptual model are represented in a layered model (Fig. 3). At the right the reused ontologies are references. In the construction of the ontologies all layers were extended with new concepts and relations. Some of dimensions of the layered model are briefly described below.

Finite Element: A widely used numerical means for finding stable solutions that approximately solve differential equation boundary value problems is the finite element method (FEM). We developed FEM ontology to describe FEM numerical model concepts and relations for simulating inner ear system based of the work of Sun *et al.* [5].

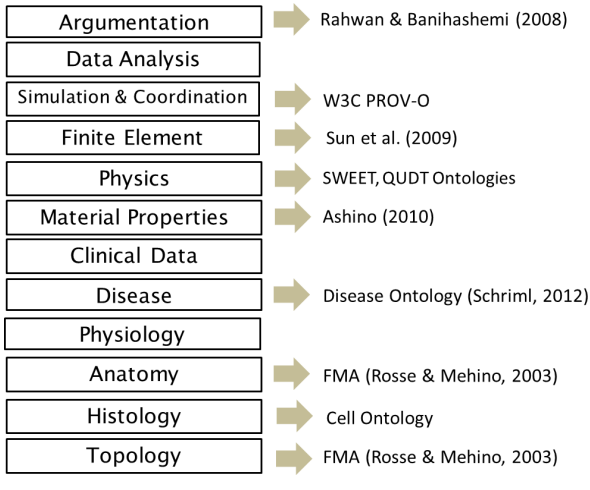


Fig. 3. Layers mapping to different domains in the conceptual model.

Simulation and Coordination: The Simulation and Coordination dimension describes the workflow behind a FE simulation. A workflow is a representation of the sequence of data artefacts, agents and processes involved in a simulation. The representation of workflows is a recurrent task and conceptual models have been created to maximize the interoperability of these workflows. These models are called provenance models due to their ability to describe the historical trail behind the generation of an artefact. The provenance workflow representation can be both prospective (the specification of a simulation workflow in the SIFEM context) or retrospective (the capture of a specific simulation workflow which was executed). The Simulation and Coordination model also defines the associated metadata for the files which are imported into the SIFEM platform (structured data files, meshs and images).

The W3C Provenance Ontology (Prov-O) [6] was used to describe both prospective and retrospective provenance workflows. While Prov-O provides the backbone of the workflow (high-level classes and properties), specific classes for SIFEM project were created to specialize Prov-O classes, such as *prv:Entity* and *prv:Activity*.

Argumentation and Reference: Every element in the simulation (from the mesh geometry and parameters, to the software artefacts used) can be annotated with user feedback. The core motivation for this dimension is to allow different users to collaborate in the dialog and criticism of the simulation models. A high-level category of argumentation predicates are used and complemented with natural language descriptors. Examples of argumentation predicates are (*agreesWith*, *disagreesWith*, *contradicts*, *supportsWithEvidence*, *accordingTo*).

Physics: The physics model layer allows a principled description of physical quantities, their relationships and associated units involved in a FE biosimulation experiment. Two main ontologies were reused, namely NASA Semantic Web for Earth and Environmental Terminology (SWEET) [7] and NASA Quantity-Unit-Dimension ontology (QUDT) [8]. Material Ontology [9] was reused to represent concepts related to material properties used in FE Biosimulation experiments.

Data Analysis: The automated analysis of experimental results is supported by the Data Analysis ontology. The Data Analysis ontology models data features which are discriminative data elements and works in coordination with a feature extraction software which detects and annotates the data with these features.

Anatomy: The micro-anatomy of the ear is detailed in the Anatomy ontology. Since SIFEM is chiefly concerned with sensorineural (or inner ear) hearing loss, rather than conductive (or middle ear) hearing loss, more emphasis is given here to inner ear anatomical structures and their topological relations rather than to those of the middle and outer ear. In the Anatomy ontology classes describe anatomical structures (e.g. *Cochlea*, *Organ of Corti* and *Reissners Membrane*) and object properties describe their topological relationships (e.g. *contains*, *bounds*, *separated from*, *separated by*, *connects to* and *connects at*). Concepts from the Foundational Model of

Anatomy (FMA) [10] are reused for most of the classes in the SIFEM Anatomy ontology. For example it has classes for such detailed inner ear structures as *afferent neurons*, *actin filaments* and *cochlear inner hair cells*. It was only necessary to define SIFEM specific concepts for extremely detailed structures such as for *inner hair cell rows* and *Hensens stripe*. Cell Ontology [11] was reused for representing concepts related to histology.

Disease: Sensorineural hearing loss can result from many causes, for example physical trauma, being in the presence of loud noises, genetic defects and from the wear and tear associated with ageing. It can also be caused by many diseases which is why there is a disease layer in the conceptual model and for this purpose Disease Ontology [12] was reused.

Physiology: This ontology provides a high level set of classes and relations to model the function of the inner ear. Examples of classes from this ontology are *Action potential* and *Travelling Wave*. Important object properties here include *hasHearingThreshold* and *hasPeakAmplitude*.

Clinical Data: It includes clinical data associated with hearing test results. Examples of types of clinical data collected related to inner ear are: Pure tone audiogram (PTA), Otoacoustic Emissions (OAEs), Auditory Brainstem Response (ABR), and Micro CT images, etc.

3.2. *Integration of different layers*

SIFEM conceptual model is designed to support simulation of hearing processes and the biological system of inner ear. The simulation of any biological system, in our case inner ear, requires two types of models; For example, models for conceptual representation of the studied phenomenon, and mathematical/numerical models for describing the behavior of the system. As illustrated in Fig. 4, inner ear system is simulated with the help of two models. Hearing models gives us conceptual representation of inner ear system from different perspectives. Geometric modelling specifies the physical structures and their relations; Mechanical modelling defines the characteristics of sound vibrations, and Electrical modelling describes the electrical responses. These three models provide complementary views for understanding same phenomenon, namely inner ear mechanics. On the other hand, Numerical model describes the behavior of a system by mathematical representations of input/output functions under various conditions. In SIFEM we employed Finite Element Method (FEM) technique to simulate modelled hearing system. Simulation gives us the simulated model of the inner ear system as output. This output need to be analysed and validated. Data analysis techniques are applied in order to understand the simulation results. Validation is carried out with clinical data gathered from real cases. After the validation step is successfully accomplished, the validated inner ear system is read for further clinical and research usages.

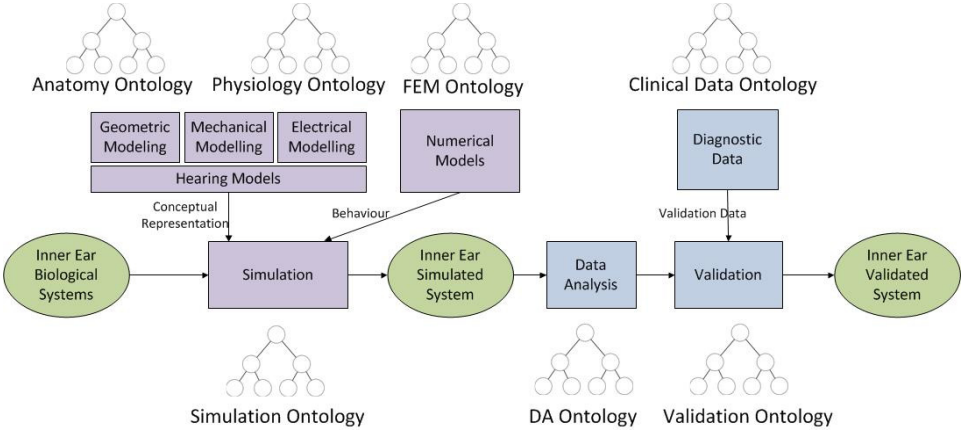


Fig. 4. Workflow of inner ear simulation and validation.

3.3. *SIFEM conceptual model*

Figure 5 depicts a conceptual representation of the FE biosimulations domain. A relatively small set of anatomical structures (classes *:AnatomicalStructure*, *:PhysicalObject*) and physical quantities (*:PhysicalQuantity*) is represented. The FE model consists in the definition of a discretised geometrical realization for each anatomical structure (a mesh) which is composed of different FE objects *:FEObject* (For example, elements, patches) and an associated physical model (*:PhysicalModel*) for the computation of the physical quantities associated to each anatomical structure. The physical quantities are computed by instantiating a physical model under a numerical method which is materialized using a specific solver program. Anatomical structures can be topologically or geometrically related to other anatomical structures and have associated material properties (*:MaterialProperty*). The computed value of the physical quantities (*:PhysicalQuantityValue*) are defined over a *:FEObject* as the *:SimulationState*, which is defined by the tuple *:PhysicalQuantityValue*, *:Position* and *:Timestamp*. The core set of classes and properties, described above, of the conceptual model represents FE objects, models and solutions.

The conceptual model also targets the representation of the data interpretation. A data view (*:DataView*) relates two or more dimensions to model the dependency between two variables. A data view is reponsible for expressing relationship between variables in the platform. The variables can be continuous (For example, *:PhysicalQuantity*, *:Position*, *:Timestamp*) or categorical (For example, *:NumericalMethod*). A data view can contain different associated features (*:Feature*). The *:Feature* has an associated *cogs:Program* which performs the process of feature extraction.

The vocabulary also describes variables, such as *:ExperimentalMeasurement* and *:DerivedValue*. *:ExperimentalMeasurement* consists of physical measurements which

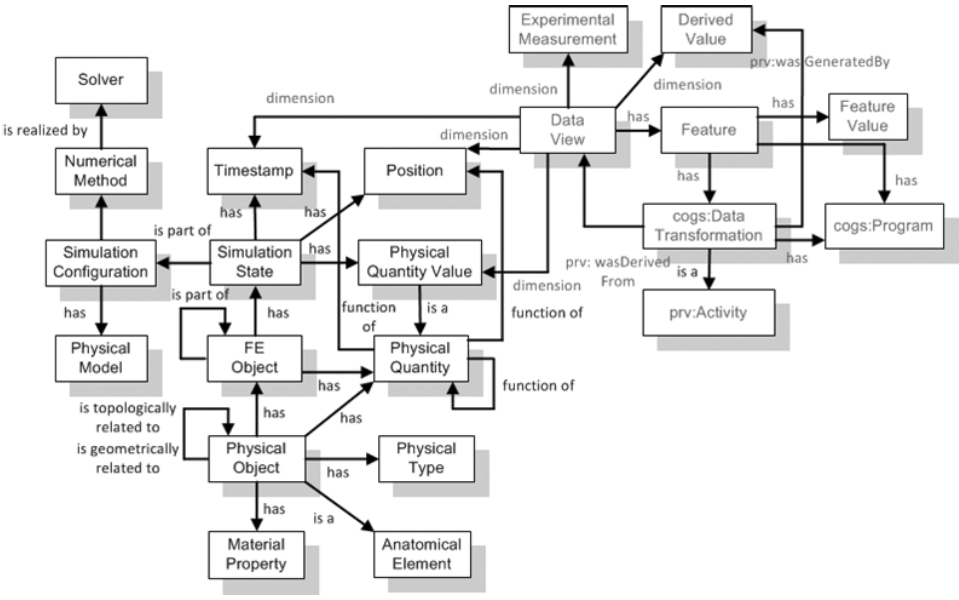


Fig. 5. Excerpt of the SIFEM conceptual model.

can be used as parameters or as validation data in the model. Examples of *:ExperimentalMeasurement* in the cochlear mechanics domain are: audiograms, measurement of otoacoustic emissions, tonotopic maps. *:DerivedValue* is a value which is derived from (*:PhysicalQuantityValue*, *:Position*, *:Timestamp*, *:ExperimentalMeasurement*) via a *:DataTransformation*. A *:DataTransformation* has an associated *cogs:Program* which does the transformation.

4. SIFEM Visualiser

SIFEM Visualiser is a Linked Data platform which aims at improving the automation in interpretation and visualisation of finite element (FE) models for inner ear (cochlea) mechanics in an integrated manner. Figure 6 represents the systematic workflow of the SIFEM Visualiser.

Input: To start with a simulation experiment, the experimenter has to provide initial inputs for the experiment. These inputs are dependent upon the Finite Element Modeling (FEM) solver which has to be used in the simulation experiment. Each FEM solver has its own input and output data formats. The experimenter specifies the inputs, such as boundary conditions (material properties), mesh type (box model, coil model), through the SIFEM Visualiser interface and is then transformed according to the solver specific input data format. The input transformation is done by representing the input data using the SIFEM conceptual model, i.e. RDFising the input data. Figure 1 shows a set of finite element input parameters,

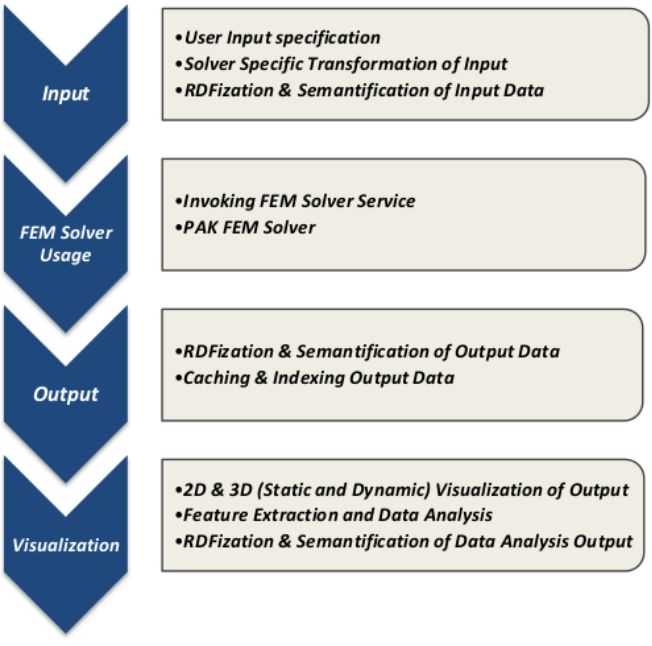


Fig. 6. SIFEM visualiser workflow.

values and their data types required in a simulation experiment. Solver specific inputs are then generated from the RDFised input data. This approach leads us to overcome the data input heterogeneity of FEM solvers and makes SIFEM Visualiser a solver independent platform. A subset of input data in RDF is shown in Listing 1.

FEM Solver Usage: Once the input parameters and their values are collected and transformed into solver specific format, the next step is to select and invoke the numerical Finite Element Methods (FEM) solver service, such as PAK,

```
@prefix dao:<http://www.sifemontologies.com/ontologies/DataAnalysis.owl#> .
@prefix fem:<http://www.sifemontologies.com/ontologies/FiniteElementModel.owl#> .
@prefix sim:<http://www.sifemontologies.com/ontologies/Simulation.owl#> .
@prefix pakFemSet:<http://www.sifemontologies.com/ontologies/FEMSettingsPAK.owl#>.
@prefix bw:<http://www.sifemontologies.com/ontologies/BoxModel#> .

bw:BoxModel1ExcitationFrequencyValue
a sim:ScalarValue;
sim:hasScalarDataValue 1000.000.

bw:BoxModel1ExcitationFrequency
a fem:Frequency;
sim:hasScalarValue bw:BoxModel1ExcitationFrequencyValue.
bw:BoxModel1Load
a fem:Load;
```

Listing 1. Example input RDF.

OpenFOAM, etc. In our use-case, we use PAK FEM Solver, and to invoke the solver, we have defined a service. This service has the provision that the experimenter can select the numerical FEM solver according to their requirements. The transformed input data is then fed to the selected FEM solver and it performs the finite element calculations on the input data and respective output is generated.

Output: The output generated by the FEM solver is in solver's native format, which leads to data heterogeneity — in terms of data interpretation using different tools (like MATLAB, RStudio, etc.). To achieve interoperability and resolve heterogeneity at the output level, the output is transformed into a standard and open format, i.e. RDF. Again, the RDFisation of output data is conducted using the SIFEM conceptual model. An example subset of output data in RDF is shown in Listing 2.

Visualisation: The next step is to show the simulation results in a graphical format and to analyse the simulation results. To do so, SIFEM Visualiser extracts the numerical results from the RDF output data to Visualise it in either two-dimensional or three-dimensional form. The output data is persisted in the triple store and is also temporarily indexed in cache. Since, visualising different parameters of simulation experiments from output, there is a need to frequently query the output, the cache thus supports by reducing the unnecessary delays caused by querying the whole triple store.

Since, performing a biosimulation is a time-consuming task, the triple store persists data generated from every simulation experiment for the purpose of reusing the simulation experiment data. For instance, if a simulation has been performed in past, the platform will retrieve it from the triple store and visualise the results rather then performing a new simulation from the beginning. Furthermore, the data persistence will help the experimenter to re-run or cross-compare different simulation experiments already performed.

As the data in triple store will increase with every new simulation experiment performed, the query execution time to fetch visualisation data will also increase. Therefore, the caching will support in order to increase query performance by

```
@prefix dao:<http://www.sifemontologies.com/ontologies/DataAnalysis.owl#> .
@prefix fem:<http://www.sifemontologies.com/ontologies/FiniteElementModel.owl#> .
@prefix sim:<http://www.sifemontologies.com/ontologies/Simulation.owl#> .
@prefix pakFemSet:<http://www.sifemontologies.com/ontologies/FEMSettingsPAK.owl#>.
@prefix bw:<http://www.sifemontologies.com/ontologies/BoxModel#> .
bw:BoxModel1ExcitationFrequencyValue
a sim:ScalarValue;
sim:hasScalarDataValue 1000.000.
bw:BoxModel1ExcitationFrequency
a fem:Frequency;
sim:hasScalarValue bw:BoxModel1ExcitationFrequencyValue.
bw:BoxModel1Load
a fem:Load;
fem:holdsValueFor bw:BoxModel1ExcitationFrequency.
```

Listing 2. Example output RDF.

```
PREFIX rdf: <http://www.w3.org/1999/02/22−rdf−syntax−ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf−schema#>
PREFIX fem: <http://www.sifemontologies.com/ontologies/FiniteElementModel.owl#>
PREFIX pak: <http://www.sifemontologies.com/ontologies/FEMSettingsPAK.owl#>
PREFIX sim: <http://www.sifemontologies.com/ontologies/Simulation.owl#>

SELECT ?xCoords ?yCoord ?zCoord ?nodes ?translationXs ?translationY ?translationZ ?ids
WHERE {
?material rdf:type fem:Material; fem:hasMaterialNumber ?y; pak:hasMaterialSettings ?z .
?z pak:MATTYPE ?materialType. FILTER (?y=1) . ?nodes rdf:type fem:Node .
?nodes fem:isNodeOf ?subDomain. ?nodes fem:hasNodeID ?ids.
?subDomain fem:makesUp ?subDomainGroup. ?subDomainGroup fem:hasMaterial ?material.
?nodes fem:hasXCoordinate ?xCoords . ?nodes fem:hasYCoordinate ?yCoord .
?nodes fem:hasZCoordinate ?zCoord . ?nodes fem:holdsValueFor ?b .
?b rdf:type fem:Translation. ?b sim:hasVectorValue ?a .
?a sim:isReal true . ?a sim:hasVectorXValue ?translationXs .
?a sim:hasVectorYValue ?translationY . ?a sim:hasVectorZValue ?translationZ . }
```

Listing 3. SPARQL query for retrieving visualisation data.

reducing the time required to execute a query. The SPARQL query used to retrieve all the necessary parameters for visualisation data from the triple store or Jena in-memory model is shown in Listing 3.

The parameters listed in the "SELECT" clause of the SPARQL query (Listing 3) and their respective values are stored in the cache while visualising a simulation experiment performed in past. However, in case of visualising a new simulation experiment, the same parameters along with their values are cached at run-time (before storing data in triple store).

To visualise the experimental data, we generate two types of graphs (2D and 3D). The 2D graphs are static (non-movable) while the 3D graphs are static as well as dynamic (movable across axis). The dynamicity or ability to move 3D graphs help the experimenter to analyse the results in a more detailed and convenient way. Figures 7 and 8 shows simulation results visualised in two-dimensional format for *displacement*[b] and *greenwood*[c] functions respectively. The graph plotted for *displacement* (ref: Fig. 7) function is against "Frequency at staples" parameter and "Distance from the cochlea apex" parameter. Similarly, the graph plotted for greenwood (ref: Fig. 7) function is against "X-Displacement" parameter and "Nodes in increasing order" parameter. Figure 9 shows a static (non-movable) 3D visualisation of parameters related to the *greenwood* function application in the cochlea mechanics. The dynamic (movable) visualisation of the same example is shown in Fig. 10, where each axis can be seen individually (X-, Y- and Z-axis from left to right respectively).

In addition to visualising individual parameters of the simulation experiment, the SIFEM visualiser is also capable of generating concrete 2D plots of results generated

[b] The displacement function, uniquely defines strain within an element in terms of nodal displacements.
[c] The Greenwood function describes the relationship between the frequency of a pure tone and the position of the hair cells measured as the fraction of the total length of the cochlear (inner ear) spiral in which it resides.

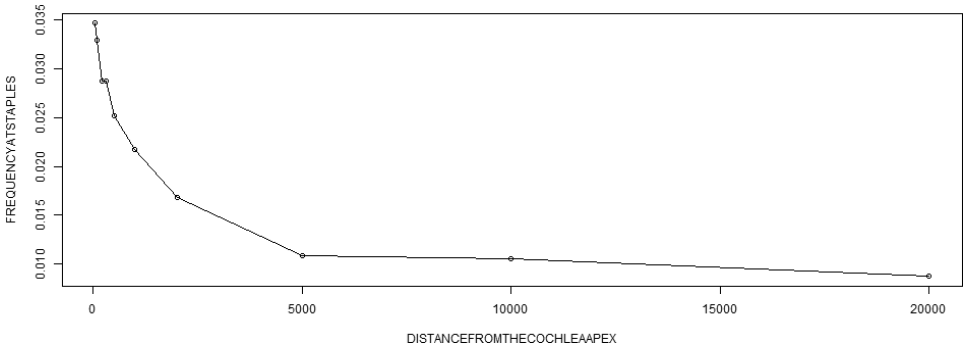


Fig. 7. 2D Visualisation displacement example.

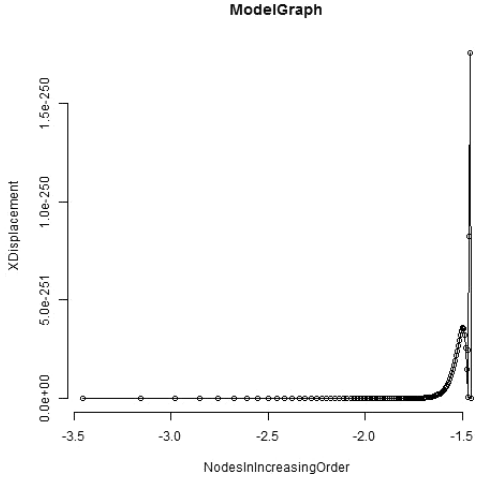


Fig. 8. 2D Visualisation greenwood example.

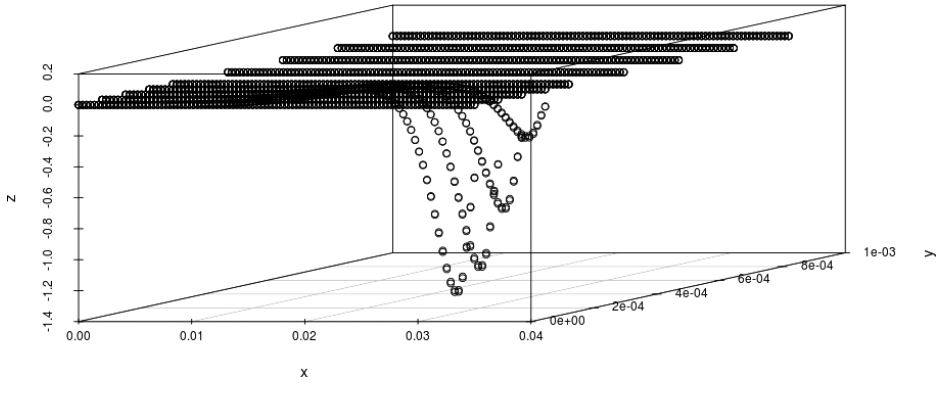


Fig. 9. 3D visualisation example (static).

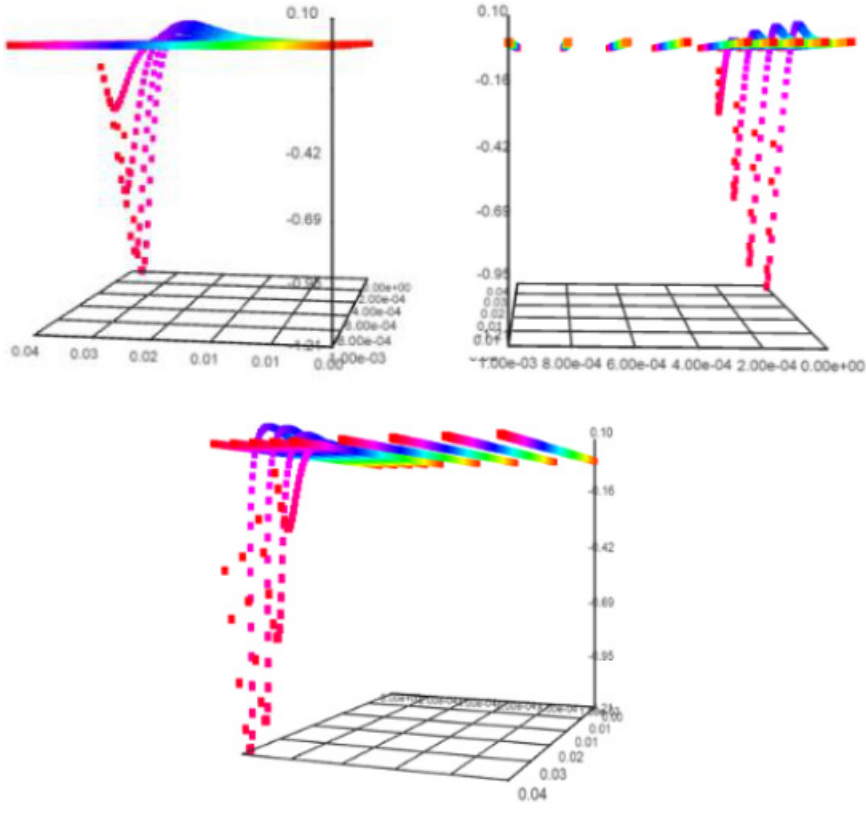


Fig. 10. Dynamic 3D visualisation example (*X*-, *Y*- and *Z*-axis respectively).

for different cochlear mathematical models, specifically "Cochlear Box Model"[d] and "Cochlear Coil Model.[e] Both box model and coil model produce results of centerline, phase and magnitude of basilar membrane as well as pressure of fluids in chambers of cochlea. These results are deemed important by the clinical practitioners and domain-experts in understanding the behavior of human cochlea.

Figure 11 shows the 2D plots of results generated from cochlear box model. The graphs are generated after the end-user has specified the geometrical parameters for the box model length of the box model, height, width, width of the basilar membrane, thickness of the membrane, material properties of basilar membrane and fluid inside the chambers, and mesh of the model. The example plots given in Fig. 11 show basilar membrane center-line, magnitude and phase of modal velocity of basilar membrane with longitudinal coupling, and pressure of fluid (real and imaginary) in

[d]The fundamental behavior of the human inner ear pressure model can be captured by a surprisingly simple box model of the cochlea by expressing it in multiple partial differential equations.

[e]Cochlea coiled model has the same mathematical model as cochlea box model acoustic wave equation for modeling fluid inside the chambers and Newtonian dynamic equation for modeling behavior of basilar membrane. However, the equations in coil model are strongly coupled.

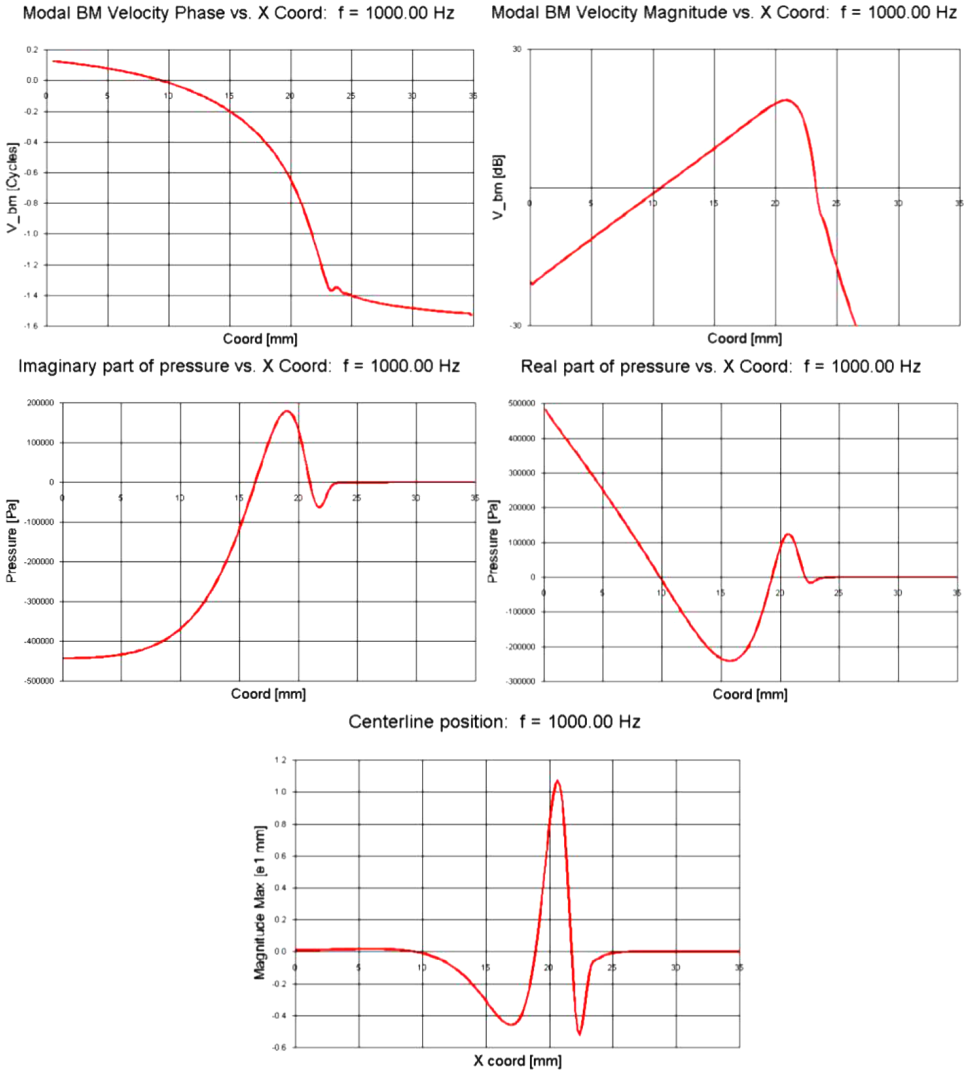


Fig. 11. Examples of data output for the simulation of the cochlear box model.

chambers with longitudinal coupling obtained with input frequency of 1 kHz for box model.

Similarly, for Cochlea Coiled Model — user can change several parameters geometry parameters and parameters of spiral, then material properties for solid and fluid, in the same manner as for the cochlea box models. The example plots given in Fig. 12 show basilar membrane center-line, magnitude and phase of modal velocity of basilar membrane with longitudinal coupling, and pressure of fluid (real and imaginary) in chambers with longitudinal coupling obtained with input frequency of 1 kHz for coil model.

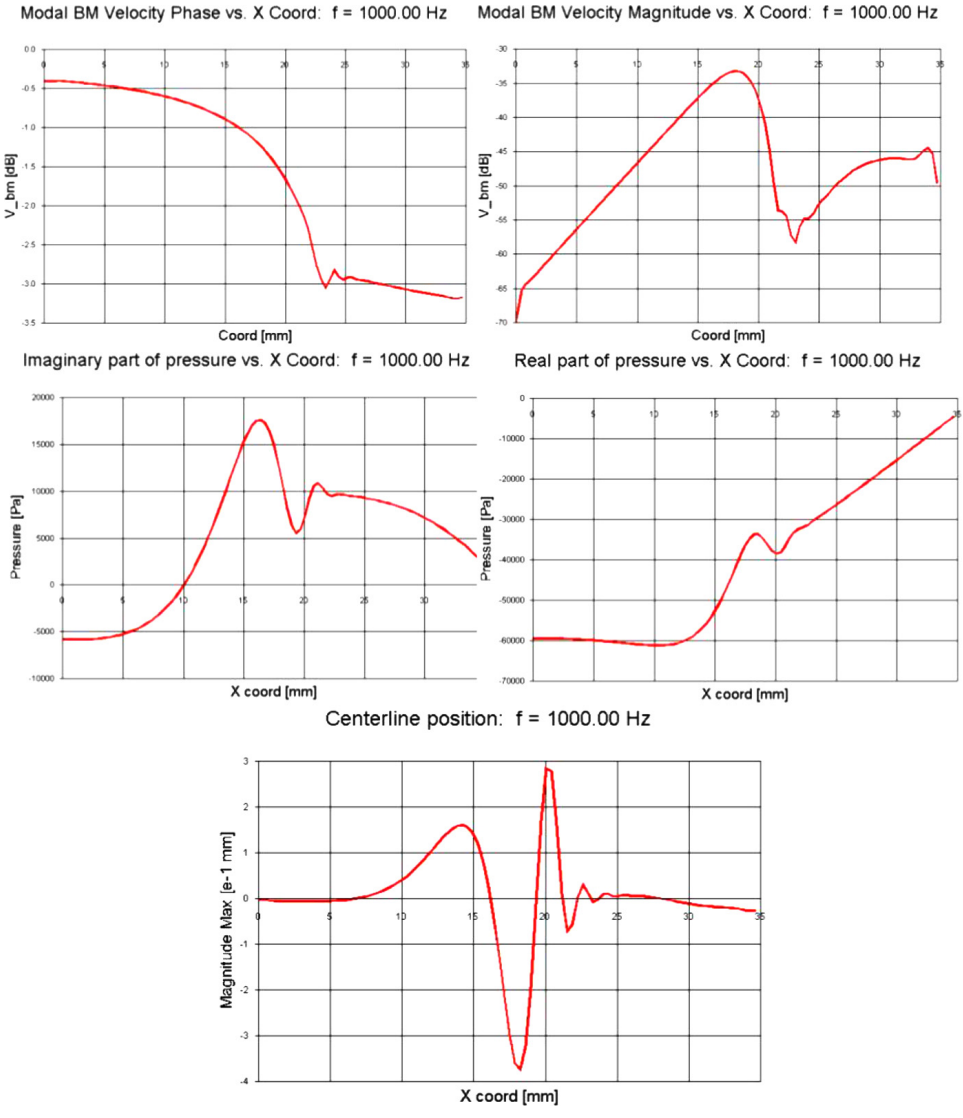


Fig. 12. Examples of data output for the simulation of the cochlear coil model.

The plotted graphs are then analysed and important features (Examples of such features are graph behaviors, such as periodic, linear etc.) are extracted from the graph. This is done by analysing the numerical data plotted in the graph. The output of the data analysis is then transformed to RDF using the SIFEM conceptual model to increase data interoperability of the SIFEM Visualiser. Example data analysis output in RDF is shown in Listing 4.

```
@prefix dao:<http://www.sifemontologies.com/ontologies/DataAnalysis.owl#> .

:DataViewBMMagnitude dao:hasDimensionX :translationX ;
dao:hasMinmumX '4.2027E−258' ;
dao:hasMaximumX '2.57604E−258' ;
dao:hasDimensionY :translationY ;
dao:hasMinimumY '2.95927E−257' ;
dao:hasMaximumY '3.59028E−257' ;
dao:hasGlobalMinima '(4.2027E−258, 2.95927E−257)' ;
dao:hasGlobalMaxima '(2.57604E−258, 3.59028E−257)' ;
dao:hasFeature dao:Periodic .
```

Listing 4. Semantic interpretation of data analysis output.

5. Evaluation

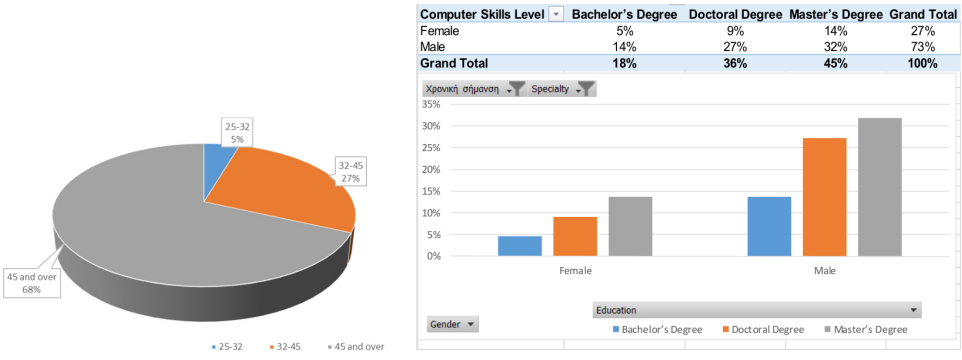
This section elaborates the results obtained from empirical evaluation of SIFEM Visualiser. We have performed both qualitative and quantitative evaluation. **To perform qualitative evaluation** of SIFEM Visualiser, the domain-experts and the clinical practitioners were involved. The primary survey was designed to address overall satisfaction and high-level quality attributes of the SIFEM visualiser. In addition to the primary survey, a more comprehensive survey was conducted. The survey consisted of four questions (tabled in Table 1) with a scoring on the scale of 1 to 5, where 1 signifies strong disagreement and 5 signifies strong agreement. And **to perform quantitative evaluation**, the experiments to record execution time of individual tasks leading to visualisation and interpretation of biosimulation experimental data were conducted in a distributed environment containing different dedicated servers. Both qualitative and quantitative evaluations were focused specifically to address the following dimensions:

Effectiveness: Unassisted task completion rate is the percentage of the users who complete the tasks without assistance from the usability test administrator. This is a high priority criterion, since successful completion of each task is the most important requirement for users.

Efficiency: Efficiency will be measured as the average number of minutes to complete each task. This is a moderate priority criterion, as the time taken by the machine is expected to be longer than the user time.

Satisfaction: Satisfaction is also a moderate priority criterion as any lack of satisfaction will reduce users willingness to continue to use the applications.

Demographics of Survey Respondents: The qualitative evaluation of the SIFEM visualiser was conducted using 2 different surveys. Both surveys were handed to the domain-experts and the clinical practitioners of different nationalities, gender, and education level. For the primary survey, we obtained around 16 responses and for the second survey, we obtained 60 responses (out of which 27 responses were from domain-experts and 33 responses where from clinical practitioners). Demographics of participants and respondents in terms of age, computer



(a) (b)

Fig. 13. Demographics — age (a) and computer skills (b).

skills, and experience in their respective field of study are shown in Figs. 13(a), 13(b), and 14.

From the total population that participated in the survey, 73% was male and 27% female. From Fig. 13(a), in terms of age, 68% of the participants were 45 years of age and over, while 5% participants were between the age bracket of 25-30 and 27% were between 32-45 years age brackets. In terms of computer skills, from Fig. 13(b), it is evident that majority of the participants were averagely-to-well versed in computer usage or skill. Almost 50% hold a Masters degree and one third a Doctoral and in terms of their experience related to domain, from Fig. 14, 60% of

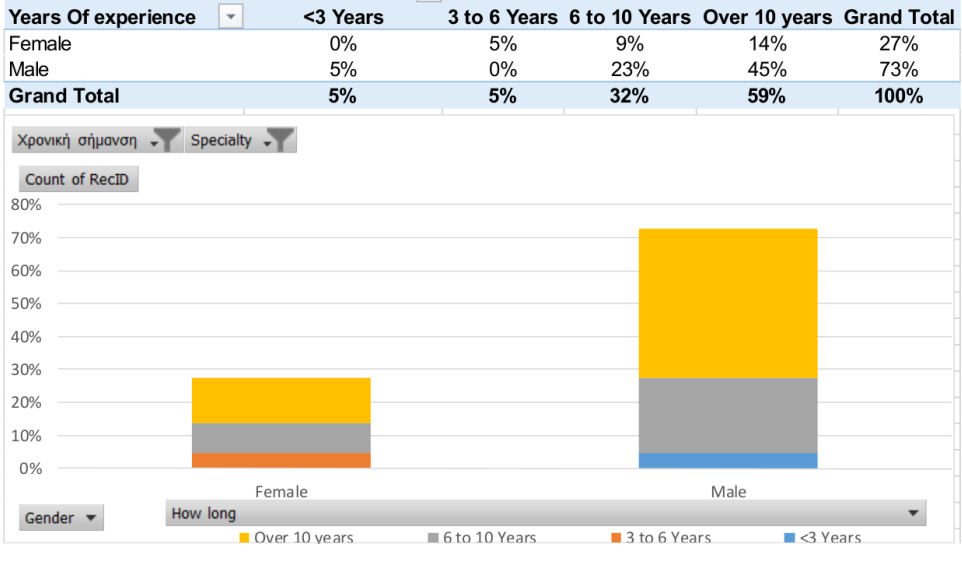


Fig. 14. Demographics — experience of domain.

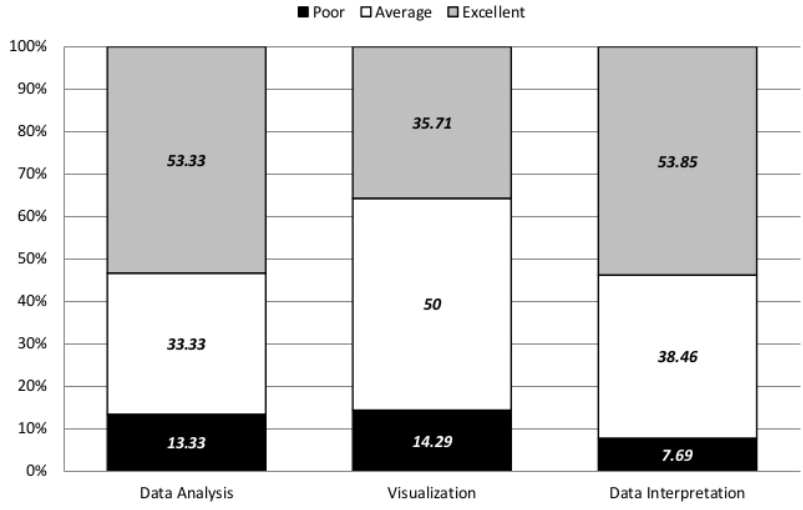


Fig. 15. Qualitative results.

the participants had over 10 years of experience in practicing cochlear mechanics and medicine.

Qualitative Evaluation: To perform qualitative evaluation, we created a survey to gather feedback from domain-experts. The survey was targeted to asses the quality of Data Analysis, visualisation and Data Interpretation. Figure 15 depicts the results of the survey. We observe and conclude in Fig. 15 that 50% of domain-experts were averagely satisfied with the visualisation results, while around 36% were extremely satisfied with the visualisation. Similarly, for both data analysis and interpretation most of the domain-experts were highly satisfied with the output.

The overall satisfaction of the users (domain-experts) is shown in the Fig. 16, where 6.7% of the users are extremely satisfied with the system and 26.7% of the users are very satisfied. Similarly, around 27% of the users are somewhat satisfied with SIFEM visualiser. It can be noted that around 14% of the users are below the satisfaction level of the system. The detailed results of the survey are available at `https://goo.gl/WCulxW`[f] and `https://goo.gl/PSvvLY`[g].

Since, the SIFEM visualiser will be mainly used by researchers, we first demonstrate results from the second survey answered by users with experience in the modelling field (domain-experts) and compare and contrast with the results of survey by medical doctors (clinical practitioners) with no experience in modelling of ear mechanics. The results of the second survey for the questions given in Table 1 are given in Figs. 17–20. The users, both domain-experts and the clinical practitioners have marked there opinion about the SIFEM visualiser by selecting between the scale of 1 to 5.

[f]Results compiled in Excel.
[g]Results compiled by SurveyMonkey.

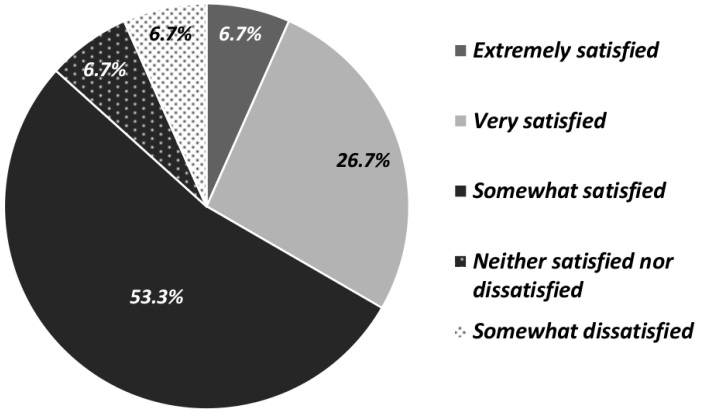


Fig. 16. Overall satisfaction.

Table 1. Survey questions.

Q1	*I think that I would like to use this system frequently*
Q2	*I thought the system was easy to use*
Q3	*I would imagine that most people would learn to use this system very quickly*
Q4	*I felt very confident using the system*

Data	1	2	3	4	5	Grand Total
Bachelor's Degree	**0%**	**9%**	**4%**	**0%**	**0%**	**13%**
<3 Years	0%	4%	0%	0%	0%	4%
3 to 6 Years	0%	4%	0%	0%	0%	4%
6 to 10 Years	0%	0%	4%	0%	0%	4%
Doctoral Degree	**4%**	**9%**	**22%**	**13%**	**4%**	**52%**
<3 Years	0%	0%	0%	4%	0%	4%
3 to 6 Years	0%	0%	0%	9%	0%	9%
6 to 10 Years	0%	0%	4%	0%	0%	4%
Over 10 years	4%	9%	17%	0%	4%	35%
Master's Degree	**4%**	**4%**	**13%**	**9%**	**4%**	**35%**
<3 Years	4%	4%	9%	0%	0%	17%
3 to 6 Years	0%	0%	0%	9%	0%	9%
6 to 10 Years	0%	0%	4%	0%	0%	4%
Over 10 years	0%	0%	0%	0%	4%	4%
Grand Total	**9%**	**22%**	**39%**	**22%**	**9%**	**100%**

(a)

Data	1	2	3	4	5	Grand Total
Bachelor's Degree	**5%**	**5%**	**9%**	**0%**	**0%**	**18%**
3 to 6 Years	0%	0%	5%	0%	0%	5%
6 to 10 Years	0%	0%	5%	0%	0%	5%
Over 10 years	5%	5%	0%	0%	0%	9%
Doctoral Degree	**9%**	**5%**	**14%**	**5%**	**5%**	**36%**
6 to 10 Years	9%	0%	0%	0%	0%	9%
Over 10 years	0%	5%	14%	5%	5%	27%
Master's Degree	**23%**	**5%**	**14%**	**5%**	**0%**	**45%**
<3 Years	5%	0%	0%	0%	0%	5%
6 to 10 Years	5%	5%	5%	5%	0%	18%
Over 10 years	14%	0%	9%	0%	0%	23%
Grand Total	**36%**	**14%**	**36%**	**9%**	**5%**	**100%**

(b)

Fig. 17. Results of Q1.

Data	1	2	3	4	5	Grand Total
Bachelor's Degree	**4%**	**4%**	**0%**	**4%**	**0%**	**13%**
<3 Years	0%	0%	0%	4%	0%	4%
3 to 6 Years	4%	0%	0%	0%	0%	4%
6 to 10 Years	0%	4%	0%	0%	0%	4%
Doctoral Degree	**4%**	**4%**	**17%**	**22%**	**4%**	**52%**
<3 Years	0%	0%	0%	0%	4%	4%
3 to 6 Years	0%	0%	4%	4%	0%	9%
6 to 10 Years	0%	0%	4%	0%	0%	4%
Over 10 years	4%	4%	9%	17%	0%	35%
Master's Degree	**0%**	**13%**	**9%**	**13%**	**0%**	**35%**
<3 Years	0%	9%	4%	4%	0%	17%
3 to 6 Years	0%	0%	4%	4%	0%	9%
6 to 10 Years	0%	0%	0%	4%	0%	4%
Over 10 years	0%	4%	0%	0%	0%	4%
Grand Total	**9%**	**22%**	**26%**	**39%**	**4%**	**100%**

(a)

Data	1	2	3	4	5	Grand Total
Bachelor's Degree	**0%**	**0%**	**9%**	**9%**	**0%**	**18%**
3 to 6 Years	0%	0%	0%	5%	0%	5%
6 to 10 Years	0%	0%	5%	0%	0%	5%
Over 10 years	0%	0%	5%	5%	0%	9%
Doctoral Degree	**5%**	**5%**	**14%**	**9%**	**5%**	**36%**
6 to 10 Years	0%	0%	5%	5%	0%	9%
Over 10 years	5%	5%	9%	5%	5%	27%
Master's Degree	**5%**	**9%**	**9%**	**18%**	**5%**	**45%**
<3 Years	0%	5%	0%	0%	0%	5%
6 to 10 Years	5%	0%	5%	5%	5%	18%
Over 10 years	0%	5%	5%	14%	0%	23%
Grand Total	**9%**	**14%**	**32%**	**36%**	**9%**	**100%**

(b)

Fig. 18. Results of Q2.

The survey results of Q1 are shown in Fig. 17, it could be appropriate to state based on the results from domain-experts Fig. 17(a) and medical practitioners Fig. 17(b) with an evaluation of 3 in the scale from 1 to 5 with cumulative response of 39% and 36% respectively that overall engagement of these parties with the application stands average. However, the opinion of experienced parties with 10 years with doctoral salutation in domain gave it 9% and 5% respectively suggests that they would involve right away with the usage of the platform.

Figure 18 shows the survey results of Q2, and it is evident that, ease of use have made domain-experts (Fig. 18(a)) and medical practitioners (Fig. 18(b)) united with the score from 1 up to 3 in the scale of 1 to 5. It would be worth mentioning that rest of the domain-experts stands on the middle ground with the score of 3 where scale remains constant.

Learning from the system and quick adoption of the system in the practice is one of the key aspects for evaluation and based on the results given in Fig. 19, for Q3, both the parties (domain-experts Fig. 19 and medical practitioners Fig. 19(b)) have suggested that they take an average to small amount of time to learn to use the proposed SIFEM visualiser. Key message from medical experts with 41% with 4 and 36% with 3 score suggested that the necessary time required for someone

Data	1	2	3	4	5	Grand Total
Bachelor's Degree	**4%**	**0%**	**4%**	**0%**	**4%**	**13%**
<3 Years	0%	0%	0%	0%	4%	4%
3 to 6 Years	4%	0%	0%	0%	0%	4%
6 to 10 Years	0%	0%	4%	0%	0%	4%
Doctoral Degree	**4%**	**17%**	**9%**	**9%**	**13%**	**52%**
<3 Years	0%	0%	0%	0%	4%	4%
3 to 6 Years	0%	0%	4%	4%	0%	9%
6 to 10 Years	0%	4%	0%	0%	0%	4%
Over 10 years	4%	13%	4%	4%	9%	35%
Master's Degree	**4%**	**9%**	**4%**	**9%**	**9%**	**35%**
<3 Years	4%	9%	0%	4%	0%	17%
3 to 6 Years	0%	0%	0%	4%	4%	9%
6 to 10 Years	0%	0%	4%	0%	0%	4%
Over 10 years	0%	0%	0%	0%	4%	4%
Grand Total	**13%**	**26%**	**17%**	**17%**	**26%**	**100%**

(a)

Data	1	2	3	4	5	Grand Total
Bachelor's Degree	**0%**	**0%**	**9%**	**9%**	**0%**	**18%**
3 to 6 Years	0%	0%	0%	5%	0%	5%
6 to 10 Years	0%	0%	5%	0%	0%	5%
Over 10 years	0%	0%	5%	5%	0%	9%
Doctoral Degree	**5%**	**5%**	**5%**	**18%**	**5%**	**36%**
6 to 10 Years	0%	5%	0%	5%	0%	9%
Over 10 years	5%	0%	5%	14%	5%	27%
Master's Degree	**0%**	**9%**	**23%**	**14%**	**0%**	**45%**
<3 Years	0%	5%	0%	0%	0%	5%
6 to 10 Years	0%	5%	5%	9%	0%	18%
Over 10 years	0%	0%	18%	5%	0%	23%
Grand Total	**5%**	**14%**	**36%**	**41%**	**5%**	**100%**

(b)

Fig. 19. Results of Q3.

to learn the to use the system. The most experienced of the doctors irrespective of the education level are the ones who advocate this view.

Any system's durability relies on cumulative confidence of the users using it based on various parameters. The results of question Q4 can be seen in Fig. 20, where the confidence score of 2 and 3 was achieved from medical practitioners with supportive participation of 45% and 36% whereas technical experts have settled with the score of 4 with 30% of participation urging to conclude that both type of users were confident in using the system.

Technological Profile: The system has been developed as JAVA J2EE Web-application using Apache Jena, Spring Framework, rJava[h], and Shiny by RStudio[i]. Openlink Virtuoso has been used as a triple store for storing RDFised FEM data and MongoDB has been used for caching and indexing purposes. The application is deployed on Wildfly[j] (JBoss 8) Application Server on a dedicated machine. Both MongoDB and Virtuoso have been hosted on two separate machines. Additionally, since the platform uses PAK Solver for performing simulation experiments, a dedicated machine, running windows OS has been used for hosting PAK Solver.

[h] https://www.rforge.net/rJava/
[i] http://shiny.rstudio.com/
[j] http://wildfly.org/

Data	1	2	3	4	Grand Total
Bachelor's Degree	**4%**	**9%**	**0%**	**0%**	**13%**
<3 Years	4%	0%	0%	0%	4%
3 to 6 Years	0%	4%	0%	0%	4%
6 to 10 Years	0%	4%	0%	0%	4%
Doctoral Degree	**0%**	**17%**	**17%**	**17%**	**52%**
<3 Years	0%	0%	0%	4%	4%
3 to 6 Years	0%	4%	4%	0%	9%
6 to 10 Years	0%	0%	4%	0%	4%
Over 10 years	0%	13%	9%	13%	35%
Master's Degree	**13%**	**0%**	**9%**	**13%**	**35%**
<3 Years	9%	0%	4%	4%	17%
3 to 6 Years	4%	0%	0%	4%	9%
6 to 10 Years	0%	0%	0%	4%	4%
Over 10 years	0%	0%	4%	0%	4%
Grand Total	**17%**	**26%**	**26%**	**30%**	**100%**

(a)

Data	2	3	4	5	Grand Total
Bachelor's Degree	**9%**	**0%**	**9%**	**0%**	**18%**
3 to 6 Years	5%	0%	0%	0%	5%
6 to 10 Years	0%	0%	5%	0%	5%
Over 10 years	5%	0%	5%	0%	9%
Doctoral Degree	**14%**	**18%**	**0%**	**5%**	**36%**
6 to 10 Years	0%	9%	0%	0%	9%
Over 10 years	14%	9%	0%	5%	27%
Master's Degree	**23%**	**18%**	**5%**	**0%**	**45%**
<3 Years	5%	0%	0%	0%	5%
6 to 10 Years	5%	14%	0%	0%	18%
Over 10 years	14%	5%	5%	0%	23%
Grand Total	**45%**	**36%**	**14%**	**5%**	**100%**

(b)

Fig. 20. Results of Q4.

Quantitative Evaluation: Table 2 shows a set of tasks in a biosimulation workflow — starting from input parameter collection to analysis and visualisation — completed in a total time of 181285 milliseconds compared to several hours taken to complete the similar workflow in a normal biosimulation environment. Usually, all the tasks in Table 2 are performed in isolated environments and take substantial

Table 2. Execution time (ms) for biosimulation tasks in a single workflow.

Task	Execution time (milliseconds)
input.cfg creation	219
input RDFization	1950
Solver execution	64233
output RDFization	4897
Querying Triple Store	**98919**
Querying in-memory Jena model	**9603**
Querying Cache	**509**
Data Analysis	738
Data Analysis output RDFization	217

manual effort to align data, models, and simulation results to complete a workflow. Since, varying simulation might have different input parameters, and different simulation functions, in order to ascertain the credibility of execution time — all the experiments were performed for a single type of simulation and function (i.e. *Displacement* function).

From Table 2, it is also pertinent to note that the caching mechanism significantly reduces the execution-time as compared to while querying the triple store or in-memory model. We employed a heuristic approach in determining the importance of a caching mechanism. We RDFised FEM output of *Displacement* function for a single simulation experiment. RDFising the FEM output produces a `7.8 MB` file, serialized as *.ttl* format. The RDFized output contains `518305` number of triples and `22630` unique entities. We loaded the generated FEM RDF output into triple store and noticed a high amount of query execution time of `98919 milliseconds` (ref: Table 2). On querying the in-memory Jena model loaded with FEM output data, the query execution time of `9603 milliseconds` was recorded. While querying the cache, the query execution time was reduced to `509 milliseconds`. This impacts the over-all execution time of a simulation experiment performed using the proposed platform. For instance, to Visualise the results of a simulation experiment for *displacement* function (after performing the simulation) takes: (1) `171 seconds` — in case of triple store, (2) `82 seconds` — in case of in-memory Jena model, and (3) `72 seconds` — in the case of using the cache.

6. Related Work

Scientists and domain-experts generally use well-established tools such as Matlab[k], R[l], etc. for the numerical computation and visualisation of biosimulation results. This works well in a closed environment where the numerical data is typically stored in a standalone machine. However, the process of integrating and visualising biosimulation results from heterogeneous, distributed and large-scale numerical data repositories is a highly complex task and an open research problem. In order to integrate such diverse numerical data sets, authors in [5] proposed an ontology-based framework for finite element analysis in a product development environment. It uses a three-stage automated finite element modeling (FEM) method to identify and classify structural configurations and analysis modeling knowledge into a set of formal ontologies described in OWL. Gennari *et al.* [1, 13] integrates and Visualise three different biosimulation models of the heart, at three different scales (i) a cardiovascular fluid dynamics model; (ii) a model of heart regulation; and (iii) a sub-cellular model of the arteriolar smooth muscle. The representation and visualisation of biosimulation models have been steadily developed in the literature (Sauro & Bergmann [14]), including CellML [15] and SBML [16]. Ontologies such as

[k]http://uk.mathworks.com/products/matlab/
[l]http://www.r-project.org/

the Systems Biology Ontology (SBO) [17] and Terminology for the Description of Dynamics (TEDDY) [17] have been used to conceptualize biosimulation and its results.

All the approaches mentioned above focus on either building and/or visualising ontologies for the finite element constructs into the various domains such as cardiovascular, product development, and systems biology. To the best of our knowledge, the proposed SIFEM Visualiser is a first linked data based initiative to develop a tool that combines together numerical parameters, models, terminologies, storage, and querying for visualising and analysis finite element biosimulation results for the human cochlea (inner ear).

7. Conclusions and Future Work

We present a linked data enabled visualiser for biosimulation experiments. We highlight the use-case of SIFEM project, specifically, to visualise FEM biosimulation experimental data of human inner ear cochlea. The platform is developed on the use-case to understand the exact pathophysiological consequences and risk factors of hearing impairment in humans. The experimental biosimulation data and models are from scientific and clinical studies about the structure-function relationship in normal and pathological cochlear. Since, the platform is still in development phases, based on the qualitative user feedback, we conclude that the satisfaction level of domain-experts for data analysis, visualisation, and data interpretation is average to well. Recall, that most of the biosimulation tasks are performed in isolation with maximum human interference and manual labor. Therefore, based on the quantitative evaluation, we conclude that we have been successful in implementing a visualisation technique, which provides an integrated environment to domain-experts for visualising and perform biosimulation experiments in minimum time (72 seconds to be precise) as compared few hours of day.

As part of the future work, we are currently working on a comparison technique which will allow users to compare different biosimulation experimental data as well as analyse the major differences between two or more 2D or 3D graphs. Furthermore, we are also working on document analysis technique to extract graphs from already existing domain-specific literature, such that the users can compare the newly generated graphs with existing ones. At the time of writing this article we are switching to beta-version 2 based on the user feedback. Therefore, we anticipate further innovative techniques to be incorporated in the platform to improve user experience of visualising FEM biosimulation data to a greater extent.

Note: The initial version of the SIFEM Visualiser is released as an open source version, the source code of ***beta-version1*** is available at: `https://goo.gl/sxePc8`. The SIFEM Visualiser can be accessed on `http://213.249.38.66:7071/Sifem/` and User-Manual on `https://goo.gl/hbTYZt`. A video, depicting a sample simulation experiment of the running SIFEM platform can be found on `https://goo.gl/wDC0am`.

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