A Natural Movement Database for Management, Documentation, Visualization, Mining and Modeling of Locomotion Experiments

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Abstract. In recent years, experimental data on natural, un-restrained locomotion of animals has strongly increased in complexity and quantity. This is due to novel motion-capture techniques, but also to the combination of several methods such as electromyography or force measurements. Since much of these data are of great value for the development, modeling and benchmarking of technical locomotion systems, suitable data management, documentation and visualization are essential. Here, we use an example of comparative kinematics of climbing insects to propose a data format that is equally suitable for scientific analysis and sharing through web repositories. Two data models are used: a relational model (SQL) for efficient data management and mining, and the Resource Description Framework (RDF), releasing data according to the Linked Data principles and connecting it to other datasets on the web. Finally, two visualization options are presented, using either a photo-realistic rendering or a plain but versatile cylinder-based 3D-model.

1 Introduction

Transferring insights on animal locomotion to technical systems is one of the oldest themes in biomimetics. Today, the control of legged locomotion is a prolific field of research, both in the life sciences and in engineering. Nevertheless, the remaining obvious performance deficits of walking machines – with regard to their biological paragons – give rise to the question why insights on animal locomotion could not be transferred more efficiently to walking machines. While there are several likely reasons for this, one of them is the problem of integrating information from different model organisms (e.g., human, cat, cockroach, stick insect), experimental methodologies (e.g., neurophysiology, biomechanics, motion capture, modeling), and levels of approach (e.g., neural networks, reduced preparations, unrestrained intact animals). In the face of the immense growth of knowledge on natural legged locomotion, it will be essential to prepare experimental results for public access, integrate results from different labs, and improve their amenability through appropriate visualization and documentation, e.g., through Linked Data. The main objective of this paper is to present a case example of such an integrated data publication with immediate relevance for the control of spatial coordination in climbing.

The case example that we choose comprises motion capture datasets on unrestrained walking and climbing trials of three species of stick insects: *Carausius morosus*, *Aretaon asperrimus* and *Medauroidea extradentata* = *Cuniculina impigra*. All three of these species are commonly used in physiological studies on invertebrate locomotion [1, 2] and have served as paragons for artificial neural network controllers of six-legged locomotion (e.g., [3]) and walking machines [4, 5]. A demonstrator sample of our data is registered for open access publication (doi:10.4119/unibi/citec.2013.3) and has been made available in May 2014. Our case example focuses on kinematic data (marker trajectories, joint angle time courses, along with a generic description of the kinematic chains), but the database structure is already laid out for inclusion of any other experimental time-course measurements, such as recordings of ground reaction forces, muscle or nerve activity, and many others.

Concerning the potential for shared use of datasets, public-access databases are the current state of the art. As yet, though public-access databases of motion capture data have been available for some time, all of them appear to concentrate on human movement sequences. Furthermore, the available datasets are particularly appropriate for studies on computer graphics and animation but, typically, are inappropriate for addressing neuroscience-related questions. This inappropriateness may be grounded in the problem that the movement of markers cannot be related to the variables controlled by the nervous system, e.g., specific degrees of freedom of real joints.

Two prominent motion capture databases are the *CMU motion capture database* of the Carnegie Mellon University (Pittsburgh, USA; http://mocap.cs.cmu.edu/) and the *HDM05 database* of the “Hochschule der Medien” in Stuttgart, Germany (http://www.mpi-inf.mpg.de/resources/HDM05/). Both of these databases have been used for various research problems in computer science, such as generating naturalistic human movement sequences from low-dimensional, behavior-specific data spaces [6], segmenting motion sequences into distinct behaviors [7], analyzing the structure of the stored motion capture data by similarity metrics [8], content-based retrieval [9, 10] and annotation [11]. Despite these achievements in computer science, existing databases have very little to offer to the neuroscience of locomotion and, therefore, to the transfer of knowledge to walking machines. In contrast, our own database comprises morphological description of the animal studied, time courses of all relevant joint angles, along with metadata about the experimental setup, etc.. As a result, the data can be compared among species, which. To the best of our knowledge, has not been done before in scientific motion capture databases. Data can be analyzed with any measure of spatial and temporal coordination within and among legs, and is suitable for benchmarking of technical walking systems.

To illustrate this, we will first present a showcase of animal locomotion data, acquired in a collaborative research project on biomimetics of autonomous locomotion (EU FP7 project EMICAB; www.emicab.eu). Based on this example, we will introduce the data structure used in the scientific analysis and the corresponding entity relationship model for a relational database (section 3). Finally, we will present two versions of visualization (section 4), and introduce the Linked Data approach (section 5).

2 Case Example: Comparative Kinematics of Insect Climbing

Insects can efficiently and reliably climb through a canopy, a substratum much more complex than any substratum that can be mastered by modern walking machines. Aiming for biomimetic control strategies for efficient and reliable climbing, we picked the whole-body kinematics of unrestrained walking and climbing insects as our case example. In the experiments, three species of stick insects were left to walk/climb across a set of stairs as described in detail by [12]. The species belong to different families of the order Phasmatodea and differ in both size and body-to-limb length ratio. Four setups with different stair height were used, thus altering the requirements for climbing in four experimental conditions.

Insects were labeled with 18 to 20 reflective markers of 1.5 mm diameter, and motion-captured using a Vicon MX10 system with eight T10 cameras (Vicon, Oxford, UK). As a result, the raw data in our database are Cartesian marker trajectories in a world-fixed coordinate system, with 200 Hz temporal and approximately 0.1 mm spatial resolution. Marker trajectories were further processed in Matlab (The Mathworks, Natick, USA), where morphological information about the animal and measurements of marker locations were included to calculate segment-fixed coordinate systems and joint angle time courses, along with secondary information such as sequences of ground contact phases (Fig. 1), step types (Fig. 2), and more. Further details about the method and calculation of secondary data are given in [12].

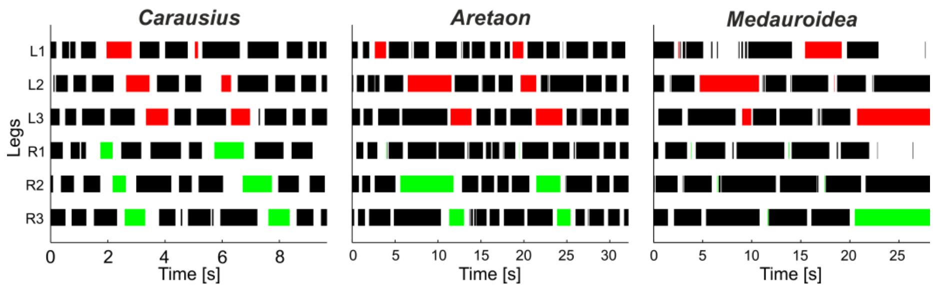

Fig. 1. Gait patterns of three species of stick insects during a climbing sequence. The colored stance phases indicate the first contacts on one of the two stairs. Same trials as in Fig. 2A.

The first three figures illustrate the kinematic complexity of unrestrained climbing behavior, reflecting the variety and detail of different kinds of kinematic analysis that are possible with our database. Fig. 1 shows a typical illustration of temporal coordination among legs. The so-called podograms show the alternating sequences of stance and swing movements of the six legs. During stance, a foot is in ground contact and the leg contributes to propulsion and stability. During swing, a foot is lifted off the ground and moved towards a new touch-down location. The colored bars mark the first stance movement in contact with a stair, thus indicating the start of a climbing sequence. Species comparison reveals that gaits are strongly irregular in all three species: stance durations and number of legs on the ground change continuously.

This irregularity is reflected also by different step types during the climbing sequences. To illustrate this, Fig. 2A shows the foot trajectories of a neighboring pair of left legs as they stepped across the setup. Here, we distinguish step types according to their lift-off and touch-down surfaces on the setup, allowing us to tell regular walking steps (type 1) from climbing steps (types 2 to 4). Note how the hind leg (HL, green) not only touched down almost exactly where its leading middle leg did (ML, red), but also how similar their trajectories were. Exceptions include two additional HL steps on stair 2 (blue arrows, *Carausius* and *Aretaon*), and two lower HL swing movements in *Medauroidea*. At present our complete database contains several thousand of walking and climbing steps, and Fig. 2B shows the relative frequencies of the different step types. Relative frequency of climbing steps (type 2-4) is lowest in long-legged *Medauroidea*. In contrast, relative freq. of steps to the side walls (type 5) is highest.

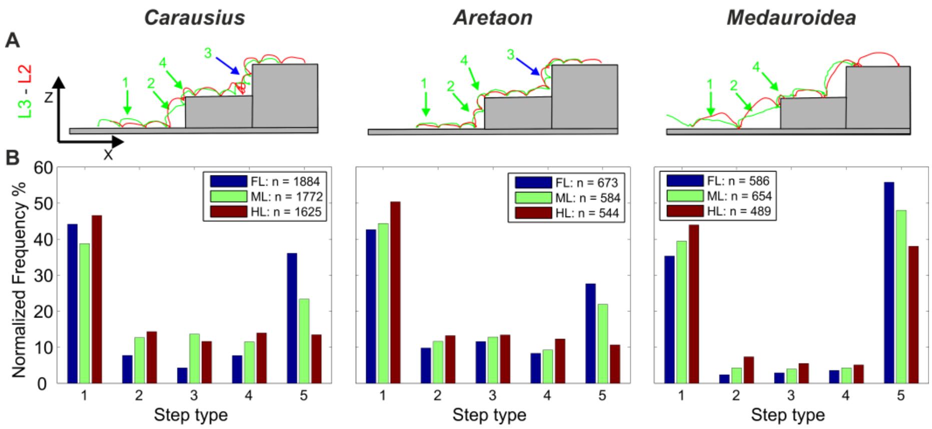

Fig. 2. Foot trajectories and step types of three insect species. A) Side views of foot trajectories of left hind leg (L3, green) and left middle leg (L2, red). Numbers label four step types, as determined by their lift-off and touch-down surfaces. Scale bars are 100 mm. B) Histograms of five step types for front, middle and hind legs (FL, ML, HL) and three insect species. Type 5 includes steps that either touched down on or lifted off from the side wall of the setup.

An important aspect of efficient climbing is the spatial coordination among legs. For stick insects, it is known that trailing legs follow the leading leg of the same body side (e.g., [13]), such that touch-down locations are very similar. It has been argued that the underlying coordinate transfer among neighboring legs is efficient because trailing legs will immediately find foothold successfully. With Fig. 3, we illustrate how our database allows comparison of spatial coordination among three species and two behavioral episodes. Based on the step type assignment as shown in Fig. 2, we can compare the accuracy of hind leg targeting for walking and climbing episodes. Accuracy is similar among species, but there is a characteristic medial offset in *Aretaon*.

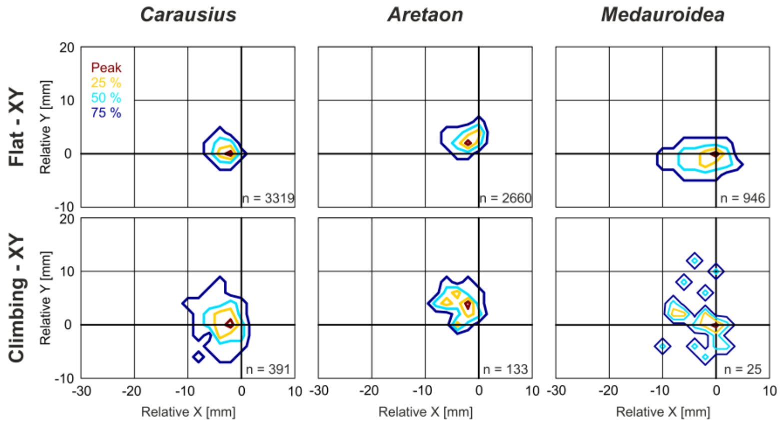

Fig. 3. Inter-species comparison of accuracy of spatial coordination. Data suitable for benchmarking of walking machines. Graphs relate pairs of leading middle (ML) and trailing hind legs (HL). Distributions of HL touch-down locations are shown with respect to the position of the ML (origin) during walking (step type 1) and climbing (step types 2/3). n: number of steps.

3 Data Structures in Matlab and MySQL

With regard to usability and functionality of the database, we were looking for

- a comprehensive, relational data model,
- suitability for multi-client graphical user interfaces, e.g. for web access,
- availability of a suitable Matlab package, allowing for immediate access from a scientific computing environment.

Based on these criteria, we opted for a relational database, using the *MySQL* database management system (http://www.mysql.com/), accessed by the administration tool *phpMyAdmin* (http://www.phpmyadmin.net) under the use of an *XAMPP* Apache server (http://www.apachefriends.org). For direct access of the database from Matlab, we chose the *MySQL database connector* (http://www.mathworks.com/matlabcentral/fileexchange/8663-mysql-database-connector).

As the main objective was to work with experimental data - in this case on animal locomotion - the data structure of the database needed to mirror the experimental procedures and to capture its conditions and results. Since each experiment may be carried out as a set of sessions, each of which comprises a number of trials, each experimental result is related to a unique trial. This trial is further specified by a given setup and subject. Different experimental conditions are described by distinct setup descriptions (e.g., to capture the height of the two stairs) or by distinct subject descriptions (e.g., if certain ablations were made). Experimental data are stored either as time courses or as spatial trajectories. Here, time courses may be any kind of real-valued variable that is measured with a given, fixed sampling rate. Trajectories, on the other hand, are time-varying three-component vectors, e.g., for describing Cartesian coordinates of marker locations in space.

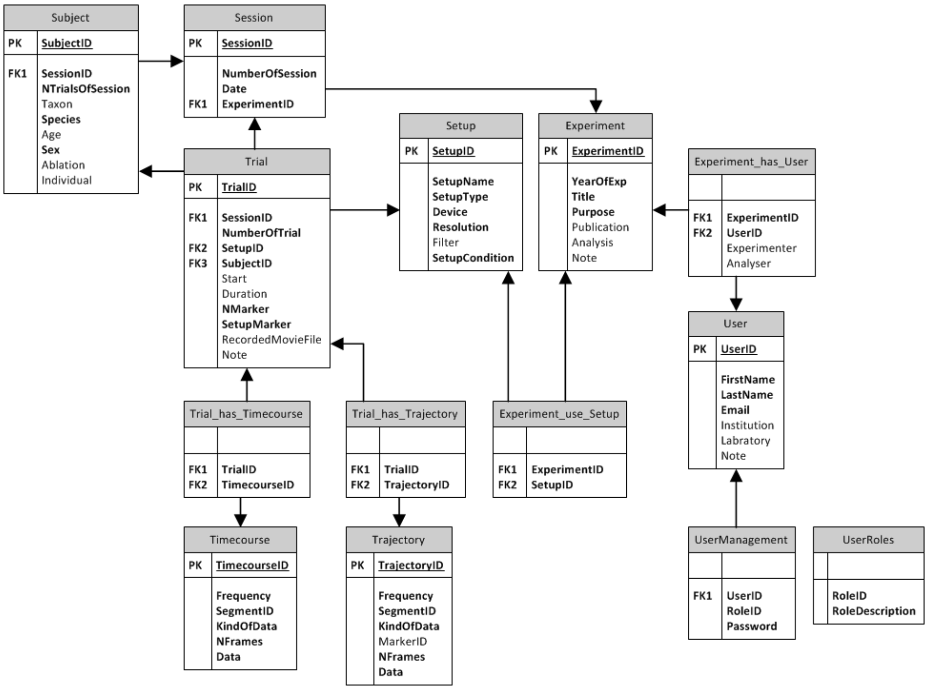

Fig. 4. Entity Relationship Model (ERM) of the database. Tables about metadata (e.g., Experiment, User, Setup) and measurements (e.g., Session, Trial, Timecourse, Trajectory). The visualization can directly access, e.g., the table Timecourse. For the complete ERM, refer to the complementary material (http://www.cit-ec.de/movement). PK: Primary Key; FK: Foreign Key.

Within the scientific computing environment Matlab, each trial was stored in a single data file. The data structure of this file was devised such that it could be applied to most, if not all motion capture experiments on insects, and could be transferred to other animal morphologies with minor adaptation (e.g., by changing segment names). The core of this data structure is the branched kinematic chain, consisting of the main body chain CS0–T3–T2–T1–Hd and up to eight side chains, namely T#.CS–R#–cox–fem–tib–tar for right legs, T#.CS–L#–cox–fem–tib–tar for left legs, and Hd.CS–ant#–scp–ped for antennae, where CS stands for 'coordinate system', T stands for 'thorax segment', ant stands for 'antenna', and # is a placeholder for the thorax segment (T1 to T3 in leg chains), or for the left and right body side (antR and antL in antenna chains). The acronyms Hd, cox, fem, tib, tar, scp and ped denote the segments head, coxa, femur, tibia, tarsus, scape and pedicel, respectively. The detailed specification of this data structure is supplied in the complementary material (http://www.cit-ec.de/movement). Most importantly, the data structure does not only store original raw data, but also computed secondary data (e.g., joint angles), as well as metadata about the experiment, user, session and setup.

Once an experiment has been analyzed in Matlab, all corresponding trial files can be uploaded into the *MySQL* database (Fig. 5), using a custom-written script that stores all variables in the corresponding database tables, according to the Entity Relationship

Model (ERM) shown in Fig. 4. Similarly, complete trials can be downloaded from the database to Matlab, e.g., for revision or further analysis.

The core of the ERM is the metadata table *Experiment* that links to the tables *User*, *Setup* and *Session*. The table *Session* then links to the tables *Subject* and *Trial*. Finally, the table *Trial* links to the data tables *Timecourse* and *Trajectory*, but also links back to the table *Setup*, thus accounting for important relation to setup conditions. Most entity attributes are stored as numbers or strings, except for the large data vectors and matrices that contain floating-point numbers, as in trajectories or time courses. The latter are stored as binary large objects (so-called BLOBs), compressing them into compact binary data structures.

Further information about the *Subject* is stored as a kinematic body model (not shown). To account for the branched kinematic chains, the table *Body* links to the table *Chain*, which, in turn, has pairwise links to the tables *Node* and *Segment*. Nodes are further specified by a sequence of rotations, accounting for the degrees of freedom; Segments may be further specified by the markers attached to them. One of the main advantages of the integrated definition of the body model is the immediate use of this information for visualization purposes.

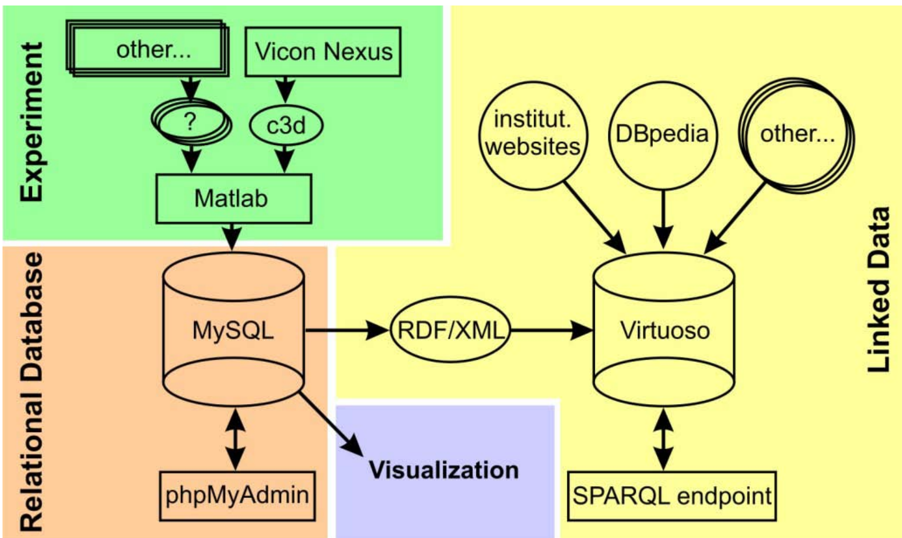

Fig. 5. Overview of our integrated approach to scientific data management, visualization and documentation. Experimental data from various sources are analyzed in *Matlab* and uploaded into a relational database (*MySQL*), from which it can be queried (*phpMyAdmin*) and visualized. Through the Linked Data approach, the database contents are transferred into a *Virtuoso* database, linking it to various web repositories. Queries are sent from a SPARQL endpoint.

4 Visualization

In order to visualize the recorded locomotion data, two different rendering frameworks have been developed: A photo-realistic offline visualization based on a geometrically accurate reconstruction of an *Aretaon asperrimus*, and a real-time visualization in a web browser, using geometric primitives (Fig. 6).

The high-quality geometric model was generated by first scanning an animal using a microCT scanner, yielding a high-resolution regular 3D array of density values. In this volumetric dataset, the insect was segmented and separated from background, and topological noise, such as small holes or tunnels, was removed by morphological operations. A triangle mesh of the outer surface of the insect was then extracted from the volumetric dataset using the Marching Cubes algorithm [14]. Since any physical measurement process inevitably introduces a certain amount of noise, the extracted triangle mesh contains high frequency geometric oscillations. This geometric noise has been removed by a few steps of Laplacian smoothing, which is a generalization of 2D diffusion flow to two-manifold triangle meshes [15]. An adaptive remeshing step [15] optimizes the triangulation to get rid of the low-quality skinny triangles produced by the Marching Cubes algorithm. The reconstructed and post-processed model is shown in Fig. 6, center. To increase the visual realism, photographs of the real insect were mapped as textures onto the surface, using the 3D modeling tool *Autodesk Maya*. This yields the final textured model shown in Fig 6, left, which consists of about 180k vertices and 360k triangles.

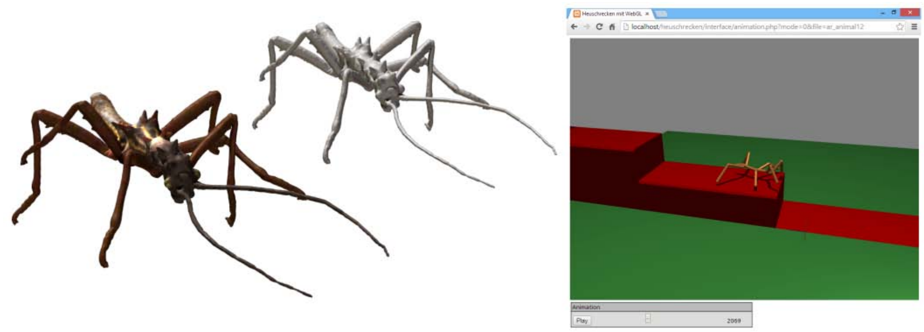

Fig. 6. Two types of visualization of insect locomotion. Left: Textured surface triangle mesh of the insect species *Aretaon asperrimus*, based on microCT scan data. Center: non-textured visualization. Right: Versatile cylinder model for real-time visualization of database content in a web browser. With its direct access to the database, WebGl visualization served as a utility test.

Also using Maya, this model was equipped with an interior control skeleton, which enables its easy animation by simply manipulating the joint angles. The skeleton was then articulated based on standard forward kinematics, and a smooth deformation of the surface mesh was computed from the updated skeleton using either linear blend skinning or dual quaternion skinning [16]. Using the recorded locomotion data to drive the skeleton articulation, and rendering the animated model using *Maya*'s global illumination technique finally results in a high-quality photo-realistic visualization, as shown in the accompanying video on the website http://www.cit-ec.de/movement.

The high-resolution model and the tool-chain described above are mainly intended for producing high-quality videos of pre-selected locomotion data, which typically requires several minutes up to an hour for rendering. As a consequence, this visualization is not suitable if a particular trial in the motion database was to be displayed. However, modern web technology enables the real-time preview of locomotion data even in a web browser, for instance when trying to find a desired motion dataset through the web-interface to our MySQL database (Fig. 5).

The enabling key technology for visualization within a browser is WebGL (www.khronos.org/webgl/), which provides interactive real-time 3D graphics to be rendered into an HTML5 canvas element. Since WebGL is a subset of OpenGL, the de-facto standard API for interactive computer graphics, it requires only moderate effort to port a desktop-based graphics application to an interactive website enhanced by 3D graphics components.

The control flow of the 3D viewer widget was implemented in JavaScript, accessing the locomotion data from the database through PHP, and visualizing the requested insect motion using a simple, flexible and efficient cylinder model. To enhance the comprehensiveness of the animation, the spatial setup was also included (Fig. 6 right). Finally, simultaneous joint angle time courses are displayed on demand (not shown).

Since WebGL can directly access the graphics hardware (GPU) through the OpenGL driver, the rendering performance of a browser-based viewer is similar to a desktop application. However, JavaScript is still too slow for animation computations such as forward kinematics and cylinder transformations. Therefore, we implement these performance-critical components as shader programs, which are executed in a massively parallel and efficient manner on the GPU. This eventually allows interactive previewing of different motion datasets in an intuitive web interface (Fig. 6).

5 Documentation and Mining by use of Linked Data

For data to be useful to other scientists, they have to be retrievable and well documented. While a relational database is a powerful tool for data management, its highly specific schema poses an obstacle to these requirements. In addition, integrating databases from different sources is a complex and labor-intensive task. This is particularly relevant for scientific datasets, which are diverse and often interdisciplinary.

Linked Data [17, 18] offers a solution to these challenges. Linked Data builds on the existing WWW and extends it with a semantic layer based on community-generated vocabularies. Linked Data can be processed by machines over large amounts of data thereby improving retrieval by search engines, and enabling queries which combine datasets from different sources. In addition, the grounding in commonly accepted vocabularies also serves human understanding of the data without the need for separate documentation. Linked Data standards (RDF, OWL, SPARQL) have been defined by the W3C consortium (http://www.w3.org/standards/semanticweb/data). Vocabularies are being developed for the description of domain-specific content. Numerous datasets from different domains are available in Linked Data.

Our goal was to translate the metadata about the stick insect locomotion experiments contained in the natural movement database into Linked Data and to test the usefulness of the approach by applying competency questions. In building the Linked Data representation we closely followed the database's ERM (Fig. 4), which had already identified the entities and possible relationships within the modeled domain. The main task in creating Linked Data is to locate suitable, established vocabularies and to identify relevant existing datasets that can be linked [19]. For convenient access of background information, our current Linked Data example integrates three sources of data:

- Metadata about the stick insect locomotion experiments
- Institutional data about researchers, organizations and publications at Bielefeld University
- DBpedia (http://dbpedia.org), a Linked Data representation of Wikipedia (e.g., supplying pictures of the species used in the experiments)

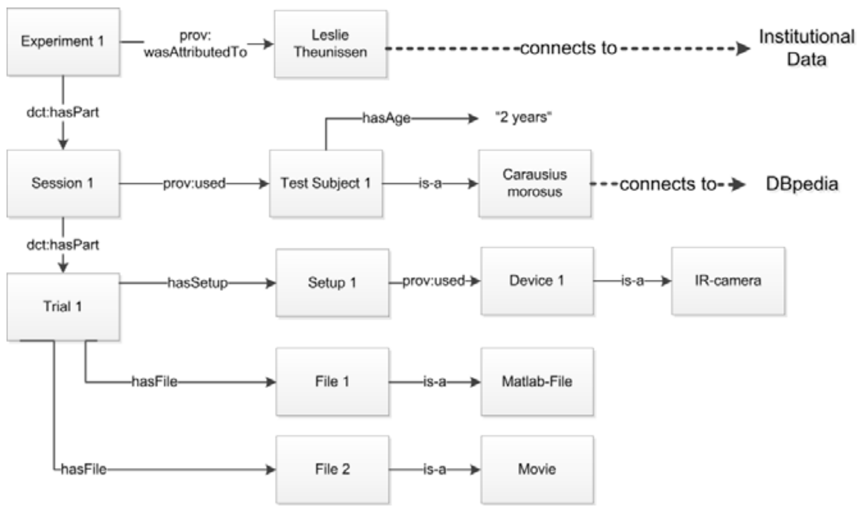

Fig. 7. Illustration of the Linked Data concept with regard to the case data (excerpt).

For data about the researchers involved, organizations and publications we used the *VIVO ontology* (http://sourceforge.net/apps/mediawiki/vivo), which combines several well-established vocabularies describing entities relevant for academic research communities. *DBpedia* already comes with its own ontology. In addition, we used the *W3C's Provenance Ontology* (http://www.w3.org/TR/2013/REC-prov-o-20130430/). Based on these vocabularies we generated the Linked Data directly from the database by means of a Perl script that exports the metadata contained in the tables experiment into RDF/XML. The export result was imported into the graph-based database *Virtuoso* (http://virtuoso.openlinksw.com/dataspace/doc/dav/wiki/Main/), which provides a SPARQL endpoint to query the data (Fig. 5). By combining the three data sources, one can answer queries that would have been impossible to answer before, such as:

1. "Give me all datasets about insects!"
2. "Which experiments were conducted by researchers from the Biological Cybernetics group?"
3. "Which publications were spawned by these motion tracking experiments?"

These queries combine information (1.) about an experiment's test species (e.g., Carausius morosus) with DBpedia entries such as the species' taxonomy (e.g., belongs to class Insecta), or (2./3.) about the experimenter with entries from institutional websites, e.g., CVs or publication lists.
Fig. 7 depicts an excerpt of the Linked Data created in this project. The vocabulary, the Linked Data itself, an endpoint to query it, and some sample queries are available on the project website http://www.cit-ec.de/movement. Because the RDF generation is fully automated, any new entries of future experiments into the Natural Movement Database will be automatically exported into Linked Data without additional effort. With its current content we have successfully answered competency questions that require different data sources. We expect the Linked Data representation to become increasingly useful in the future, as more datasets are released and can be integrated into this framework. In a next step, we consider creating Linked Data not just of the metadata but of the actual data.

6 Conclusions

We propose a Natural Movement Database suitable for large and diverse, multivariate datasets on arbitrary movement sequences. Although, in its present form, it has been devoted to insect locomotion, the key features of the data management, visualization and documentation system apply to arbitrary movement sequences of segmented limbs and/or bodies, e.g., the human hand. Major advantages of our approach are (i) the integrated storage of metadata, raw data and computed/processed data; (ii) the suitability for any kind of measured time courses, e.g., electrophysiological recordings; and (iii) the enhanced comprehensiveness through visualization and the Linked Data approach.
The dataset used for our case example has been successfully used to evaluate a novel time series data mining method [20]. Apart from such research topics in computer science, we expect great benefit for various research issues in the neuroscience of motor control. For example, the potential for pooling data across labs and experimental approaches may allow an integrated view on datasets, each of which may be limited to a small number of trials and/or relatively short recording periods (e.g., for methodological reasons). As one of the next steps, we invite colleagues to contact us about sharing their data for integration in our database. Thus, by increasing available sample sizes and numbers of parameter combinations, we hope to boost the power of statistical analyses in the face of natural variability of behavior.
Finally, the database is a valuable tool for benchmarking of modeling studies in software and hardware – revealing the discrepancies between natural and technological performance.

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