DOI: 10.1111/j.1467-8659.2009.01681.x

Eurographics/ IEEE-VGTC Symposium on Visualization 2010
G. Melançon, T. Munzner, and D. Weiskopf
(Guest Editors)

Volume 29 (2010), Number 3

Visual Analysis of Multi-Joint Kinematic Data

Peter R. Krekel[1,2], Edward R. Valstar[1,5], Jurriaan de Groot[3], Frits H. Post[2], Rob G. H. H. Nelissen[1], Charl P. Botha[2,4]

[1] Biomechanics and Imaging Group, Leiden University Medical Center
[2] Computer Graphics, Delft University of Technology
[3] Department of Rehabilitation Medicine, Leiden University Medical Center
[4] Divison of Image Processing, Leiden University Medical Center
[5] Biomechanical Engineering, Delft University of Technology

---

Abstract

Kinematics is the analysis of motions without regarding forces or inertial effects, with the purpose of understanding joint behaviour. Kinematic data of linked joints, for example the upper extremity, i.e. the shoulder and arm joints, contains many related degrees of freedom that complicate numerical analysis. Visualisation techniques enhance the analysis process, thus improving the effectiveness of kinematic experiments.

This paper describes a new visualisation system specifically designed for the analysis of multi-joint kinematic data of the upper extremity. The challenge inherent in the data is that the upper extremity is comprised of five cooperating joints with a total of fifteen degrees of freedom. The range of motion may be affected by subtle deficiencies of individual joints that are difficult to pinpoint. To highlight these subtleties our approach combines interactive filtering and multiple visualisation techniques.

Our system is further differentiated by the fact that it integrates simultaneous acquisition and visual analysis of biokinematic data. Also, to facilitate complex queries, we have designed a visual query interface with visualisation and interaction elements that are based on the domain-specific anatomical representation of the data. The combination of these techniques form an effective approach specifically tailored for the investigation and comparison of large collections of kinematic data. This claim is supported by an evaluation experiment where the technique was used to inspect the kinematics of the left and right arm of a patient with a healed proximal humerus fracture, i.e. a healed shoulder fracture.

---

1. Introduction

Kinematic data describes the movement of limbs and is used in biology, sports, orthopaedics and rehabilitation medicine. The data is generally acquired using motion tracking systems, imaging systems or computer simulation. Examples of motion tracking systems are Optotrak (Northern Digital Inc., Waterloo, Canada), which uses optical sensors, and Flock of Birds (Ascension Technology Coorporation, Burlington, USA), which uses electromagnetic sensors. The acquired kinematic data is used to monitor surgical interventions or to help answer fundamental research questions on kinematic behaviour.

Despite the widespread use of kinematic analysis methodologies, creating visual representations of motion data that support clinically relevant conclusions is challenging. The most common method for depicting kinematic output is the angle-angle plot. This is a two-dimensional plot that displays how a certain joint angle relates to another joint angle. See Figure 1 for an example of a series of standard angle-angle plots. Angle-angle plots are limited to depicting two parameters, even though joint kinematics are often correlated in three or more dimensions. For complex research questions this may result in a large number of angle-angle plots. For example, one publication by De Groot et al. includes a total of 27 angle-angle plots [De 97]. In our opinion these plots are functional when exact numerical values and relations are required. However, for the exploration of kinematic data alternative representations may be more informative.

This inspired us to create a system for the analysis of com-

Published by Blackwell Publishing, 9600 Garsington Road, Oxford OX4 2DQ, UK and 350 Main Street, Malden, MA 02148, USA.

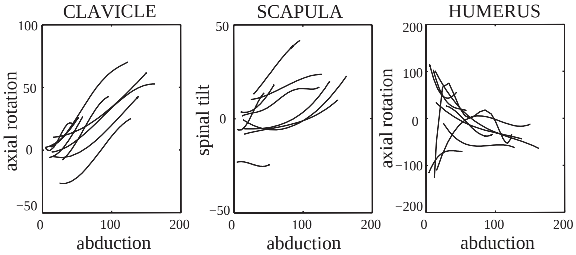


Figure 1: *An example of three angle-angle plots. These plots show the relation between elevation of the arm (abduction) and other angles of three joints of nine subjects. Image courtesy of Frans Steenbrink.*

plex, multi-joint kinematic data that gives insight in relationships between joint angles that would otherwise require a predetermined hypothesis. In order to assist this process, we have employed both forward and inverse visual query techniques in our framework. With the former, researchers can inspect the range of motion of multiple joints and find the relationships between the available DOFs. With the latter, the joint configurations that were used to reach a queried location are extracted, functionality that is useful in investigating for example compensatory kinematics in pathological joints. We believe that this system could eventually lead to new observations and different focus with respect to kinematic coupling of degrees of freedom (DOFs).

The contribution of this work is a comprehensive new approach to the visual analysis of complex multi-joint kinematic data. To the best of our knowledge, visual analysis techniques have not yet been proposed for this type of kinematic data. Novel characteristics of this approach include the following:

- Our system integrates real-time visualisation and acquisition. In other words, the visualisation process starts during data acquisition, enabling the operator to steer the acquisition process, guided by conclusions drawn from the visual analysis.
- Our forward visual query interface combines interaction and visual feedback in an integrated anatomical representation, allowing users to perform complex queries in a recognisable and therefore straightforward manner.
- We demonstrate the utility of our work on the kinematic data acquired of a proximal humerus fracture patient.

Supporting our main technical contributions, the complete implementation of this approach is available as open source at the following URL: `http://fobvis.googlecode.com`.

The remainder of this article is structured as follows: in Section 2 we discuss existing literature on kinematic data visualisation. In the subsequent section we describe our visualisation framework, including the kinematic model and filtering mechanisms that we apply. In Section 4 we describe an evaluation experiment. For this experiment we recorded the motion patterns of a subject with a healed shoulder fracture and demonstrate that the visualisation framework enables researchers to analyse the recorded motion patterns in great detail. Lastly, we discuss the contributions and limitations of our system and conclude with a prospect on future work.

2. Related Work

Much of the research on kinematic analysis finds its origins in gait analysis, the study of locomotion [Whi06]. Many improvements to the standard angle-angle plot originate from this field. For example, by adding a third dimension to the plots, an additional parameter can be visualised [MCHS05]. In addition, by color coding the graphs, another parameter can be added, resulting in a total of four parameters of a motion recording that can be visualised [MS04]. The drawback of these approaches is that the straight-forward addition of the third dimension unnecessarily complicates the interpretation of the data. Also, using colour to represent a continuous parameter is ill-advised, especially if this channel could later be useful for example to distinguish between patient measurements, a categorical parameter [Mac86].

The work most related to our research is that of Keefe et al. [KERC09]. Their visualisation system is an excellent example of how a multiple-view approach effectively shows relationships within kinematic data. Using small multiples they visualise cycles of motion of pig jaws during eating. Although many parallels exist between their and our work, their visualisation technique is specifically targeting sequential data, whereas in our data we are interested in visualising the relationships between multiple connected joints. Similarly, Chen et al. used the approach of small multiples for the cyclic patterns of bat wings during flight [CFSL07]. Although they use many markers on the bats' wings, there is no joint decomposition with subsequent analysis of a multi-joint kinematic model.

With regards to range of motion visualisation for the upper extremity there are several examples of applied visualisation techniques. A basic approach is presented by Ct et al., who use 2-D projected stick figures to show the kinematic results of a hammering task [CRM*05]. This visualisation suffices when looking at joint height, but does not reveal the kinematic relationships.

In previous work we presented a technique for visualising range of motion of the shoulder joint [KBV*06]. The described pre-operative planning system visualises the simulated range of motion of the glenohumeral joint with a moveable prosthesis. Although the comparative visualisation techniques are effective for the glenohumeral joint, these techniques do not hold for the analysis of a multi-joint kinematic chain. The main reason for this is that most joints do not function as ball-and-socket joints.

Van Sint Jan et al. presented an interesting system that visualises the kinematics of multi-joints [VCR98] . Their work uses computer tomography along with kinematic recordings to link bone morphology of the fingers to kinematics. Their visualisation method is limited to 3-D playback of the kinematics using patient-specific surface models.

Analogue to path planning techniques in robotics, a multi-joint chain can be described in configuration space [BL91, LP90]. The term *configuration* refers to a single pose of the chain of joints. The individual joints have a local range of motion that determine the total set of possible configurations, i.e. the configuration space. Our system is built around this concept, with separate views and filtering mechanisms for the DOFs of the joints and for the total range of motion of the limb.

In literature, similar visualisation approaches exist, for example Abdel-Malek et al. [AMYBT04] and Lenarčič et al. [LK06], who describe multi-joint kinematic models with accompanying visualisations of the configuration space or reachable arm space. An interesting supplement to these references dates back to 1955, where a similar range of motion visualisation technique was used to design aeroplane cockpits [Dem55]. Although these visualisations give insight in the reachable arm space, they do not disclose the underlying kinematic dependencies. To our knowledge, no technique exists that visualises both the DOFs of a kinematic model and the resulting functional range of motion.

3. Methods

3.1. Requirements Analysis

To catalogue the requirements of an improved approach to visualising range of motion measurements, we used the Delphi method [RW99]. Two human movement scientists and four orthopaedic surgeons of different clinical institutions, reflecting our target audience, were questioned using a list of propositions and a number of example visualisations. The complexity of the propositions varied, ranging from ‘Quantifying measurements is more important than visualising them’ to propositions as ‘I can use this example visualisation to track the progression of a muscular deficiency’.

Important conclusions that followed from this questionnaire were the following:

- Clinicians prefer more intuitive visualisations, whereas human movement scientists prefer visualisations that give access to more quantitative information, regardless of the additional clutter that comes with this information. All of the clinicians indicated that they were willing to use only the most simple visualisation in their conversations with patients, fearing that any visualisation other than a simple shoulder picture would be too difficult to understand for the average patient. To accommodate this requirement, a clear distinction is made throughout this work between visualising a subject’s function and visualising the range of motion of individual joints.

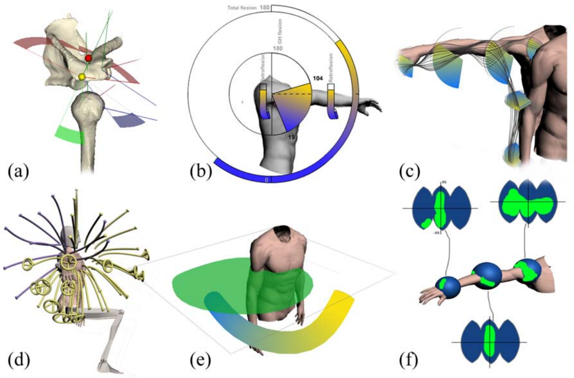


Figure 2: *Visualisation concepts that were presented to the participants of the questionnaire. Participants were asked to rate several aspects with regards to clarity and usefulness before and after an explanation was given. See Section 3.1 for a description of the subfigures.*

- With respect to the possible benefits of a new visual analysis system, participants indicated that assessment of pathology, follow-up of patients and communication with colleagues were of foremost importance.
- Due to time constraints, clinicians would be willing to spend only a few minutes analysing the kinematic data. This introduces the requirement that a kinematic visualisation technique has to be fast and intuitive.
- The reachable arm space visualisation by Lenarčič et al. (see Section 2), used as an example visualisation, was thought to be very useful. A similar visualisation disclosing more details on the separate joints was expected to fulfil most of the requirements.

Figure 2 shows some of the visualisation concepts presented to the participants of our questionnaire. The proposed visualisations were the following (see figure):

a. An integration of the DOF values with the animated bone model representation. We have implemented this technique and discovered that occlusion and continuously changing coordinate systems make this visualisation counterintuitive.
b. A schematic 2-D plot of the various parameters. This concept was eventually extended and implemented in our 3-D Pose View (see Section 3.5.2).
c. Integration of the parallel coordinates plot with the spatial location of the joints. Although this would make the semantics of the plot more intuitive, it was expected that the anatomical location would complicate the visual representation and hence understanding of relations between angles.
d. A segment visualisation with various types of endpoints to depict parameters. This view merges the visualisation

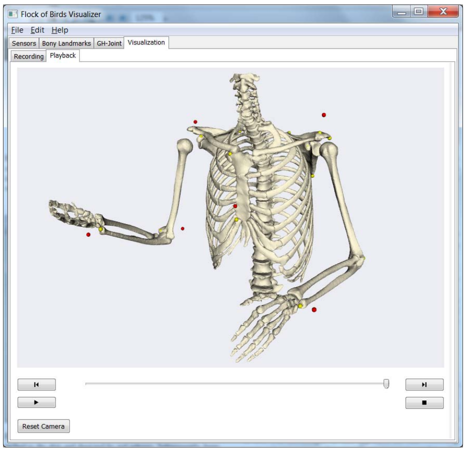


Figure 3: *The FobVis motion tracking software. Sensors are attached to the skin and depicted by red spheres. Subsequently, bony landmarks are registered relative to these sensors and depicted by yellow spheres. The surface models are rigidly transformed in accordance with the sensors and their respective bony landmarks.*

of individual joint angles and the total functional range of motion. We consider this undesirable because each answers a different set of research questions.

e. Volume visualisation with a slice-viewer and visualisation method to depict trajectories. For this specific application, volume rendering would not contribute any specific advantages. Furthermore, the conversion to volumes would unnecessarily complicate the interactivity of our system.

f. A spherical representation of the joint, mapped to a 2-D plot. Not all joints are spherical joints, making it hard to defend this visual encoding. In addition, this representation only allows for two degrees of freedom (DOFs) per joint.

Although these visualisation techniques were not used, various aspects were extracted and incorporated in the final visualisation system described herein.

3.2. Software

The software used to record shoulder motion is FobVis, a package developed by our institution. FobVis is currently built for the Flock of Birds electromagnetic system, but the generic design facilitates the use of other motion tracking systems, for example Optotrak. It has been implemented as a state machine, the transitions between states reflecting the motion tracking procedure described below. Figure 3 shows a screenshot of FobVis.

The work described in this article is implemented as a module in the FobVis software and directly uses the recorded data as input for kinematic analysis. Both the FobVis software and the visual analysis module are available as open source.

3.3. Motion Tracking

Motion tracking was performed using the Flock of Birds motion tracking system. The workflow for recording motion is in accordance with Kontaxis et al. [KCJV09] and consists of the following steps:

1. Sensors are attached to the body of the subject.
2. The positions of prominent bony landmarks relative to the sensors are registered using a motion tracked pointing device.
3. The subject follows the movement instructions of the researcher, during which the positions and rotations of the sensors are recorded. In combination with the bony landmark positions relative to the sensors this gives sufficient information to track motion of the bones, with a small error due to the sensors being attached to the skin rather than to the bones.

In common motion recording protocols, the subject is instructed to make specific movements that are expected to answer the research questions under investigation. Our technique is based on the principle that as much data should be collected as possible. The acquisition process is closely monitored by the operator, assisted by the real-time visualisations of our system. After the acquisition, the investigator can filter data and focus on the specific type of movements he would like to see. The advantages of this approach are that recording motion is not restricted to specific movements, making the recording procedure less error-prone. In addition, the investigator can pose additional research questions after doing the measurements, as a large collection of motion data is included in the visualisation.

The motion recording system is continuously updated at 25 frames per second, giving immediate feedback to the researcher. This allows the researcher to determine when enough data has been gathered by inspecting the visualisations.

3.4. Kinematic Model

Kinematic models of the human body usually consist of a hierarchical structure of kinematic chains. A kinematic chain is a series of linked rigid body segments connected by joints with one or more rotational degrees of freedom. The motion of a kinematic chain is defined by the link lengths and the variation of joint angles. The lengths are assumed to be constant for a given individual, so the postures and motions can be completely described by the joint angles.

Different kinematic models can be used to analyse motion data. We have defined our kinematic model in accordance with the authoritative work on upper extremity kinematics

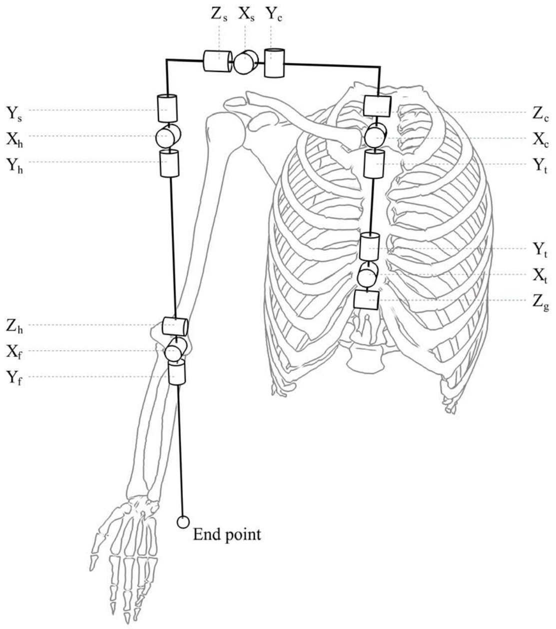


Figure 4: *Kinematic model as used within our system. The chain of rotations along various axes begins at the spine and terminates at the hand. The character g refers to the global coordinate system; t, c, s, h and f refer to the thorax, clavicle, scapula, humerus and forearm coordinate system respectively. The model is completely described in Wu et al. [WvV*05].*

by Wu et al. [WvV*05]. The assembly and connectivity of the modeled joints is depicted in Figure 4, rotations starting at the first degree of freedom of the spine and terminating at the last degree of freedom of the elbow. Quantified angles are defined relative to the proximal (preceding) joint as well as relative to the global coordinate system. These angles are calculated in real-time as motion data is acquired.

3.5. Visualisation and Filtering

Multiple linked views are used to analyse the kinematic data (see Figure 5). The degrees of freedom View, or DOF View, shows the local range of motion of each of the DOFs of the individual joints. The Pose View is used to depict the total functional range of motion of the multi-joint configuration, as well as spline curves to see a time window around poses. A parallel coordinates plot is used to quantify relationships between the parameters of the kinematic model. In addition, an unlimited number of 2D plots of data values over time can be added. Lastly, scatter plots can be generated. The different views are discussed below.

During acquisition all views are continuously updated, providing interactive feedback on the motion data acquired. Large differences in range of motion are noticable, but generally and especially when working with large datasets, the number of visible poses is too large to disclose valuable information. Visualisation and filtering form an integrated system that allows the user to analyse and compare large collections of complex kinematic data.

To find interesting characteristics of the data the researcher may want to omit data outside of a given range of a specific DOF, inspect recordings that go through a point in space or select a certain time range of the recordings where something occurred that he found interesting. For this purpose a number of filters were implemented. Filters can be activated or deactivated, depending on the requirements of the intended task. The user interface components of each of the filters are integrated in the visualisation of the kinematic aspect the filter acts upon.

Two motion recordings can be loaded simultaneously, allowing for comparison of datasets. Examples are pre- and post-operative measurements, left and right shoulders or a (bundled) group of patients suffering from the same pathology, compared to an equally large group of healthy subjects. Motion recordings are assigned different colors and adjust their alpha blending in each of the views in accordance with the number of poses that are visible to optimize the amount of information shown.

In the following subsections, we discuss each of the views of our application, first focusing on the chosen visual representation and then detailing the filtering possibilities for that view.

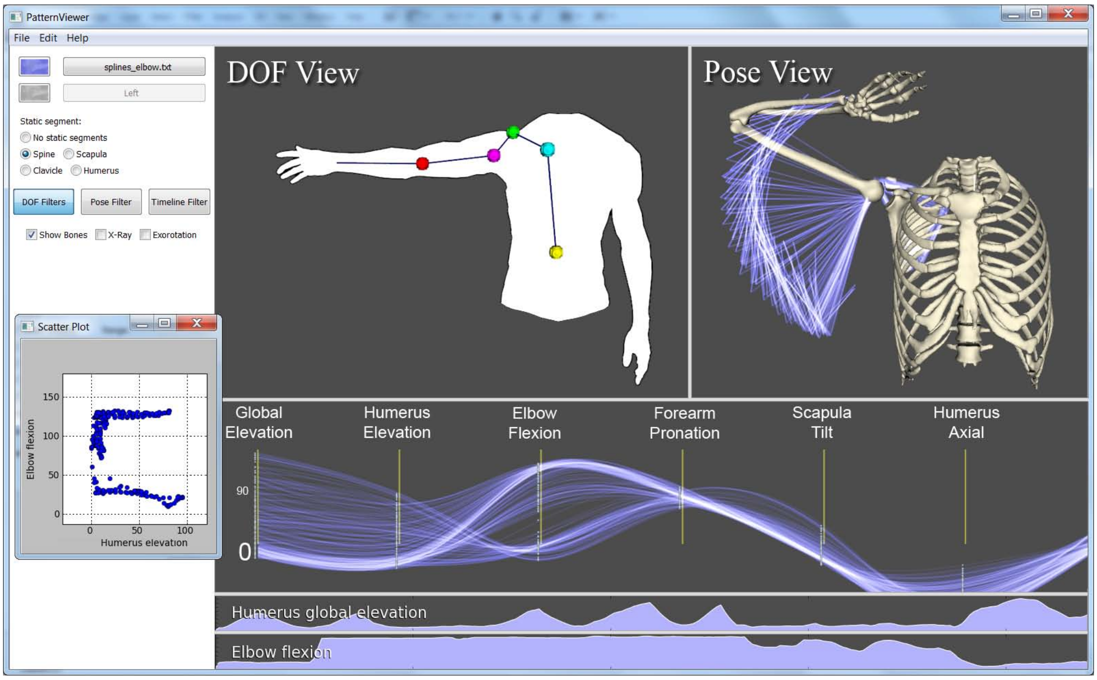
3.5.1. DOF View

To determine how datasets are different from one another, researchers will generally be interested in how the DOFs vary in relationship to other DOFs. In the DOF View these range of motion intervals are depicted in the form of joint widgets (see Figure 6). Joint widgets can be added by selecting a joint node and indicating which kinematic parameter is of interest via a popup menu. The widget shows the minimum and maximum value of the selected parameter for each of the active datasets. To prevent clutter, joint widgets can be collapsed by selecting their centerpoint.

Besides visualising the range of motion of a DOF, joint widgets also function as the user interface element of DOF filters. These are used to hide kinematic data in the linked views, filtering the data based on a selected range of the concerning DOF. The joint widget contains an orange pie-shaped figure, its adjustable size modifying the filtered range. Interaction with the widget updates the linked views, showing only the kinematic data that passed *all* of the DOF filters.

3.5.2. Pose View

In the Pose View the recorded poses are displayed as simple line drawings (see topright of Figure 5). Joints can be dis-



Static segment:
○ No static segments
● Spine ○ Scapula
○ Clavicle ○ Humerus

☑ Show Bones ☐ X-Ray ☐ Exorotation

Figure 5: *A screenshot of the system. The DOF View visualises the individual DOFs of the different joints on demand. The Pose View shows the recorded poses and thus visualises the functional range of motion. The parallel coodinates plot visualises the interrelationships between DOFs. At the bottom of the interface 2D plots of data values over time can be added. Lastly, a number of scatter plots can be in visualised in a separate frame.*

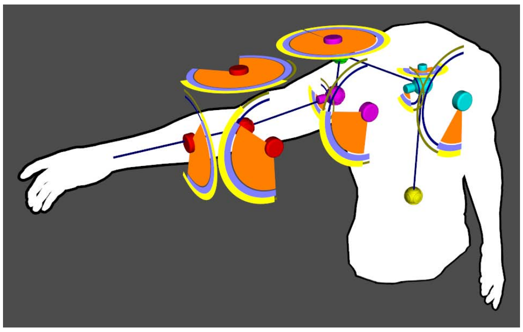


Figure 6: *The DOF View. Initially this 3D view only displays the silhouette of a human torso with a schematic representation of the predefined connected joints. By selecting joints the user can add visual representations of the range of motion of the DOFs as defined by the applied kinematic model. For each of these DOFs a joint widget is added that includes a blue and a yellow bar representing the range of motion of two different datasets. The orange pie-shaped parts are DOF filters, used to display only a part of the data in the linked views. To prevent clutter joint widgets can be collapsed by selecting their centerpoint.*

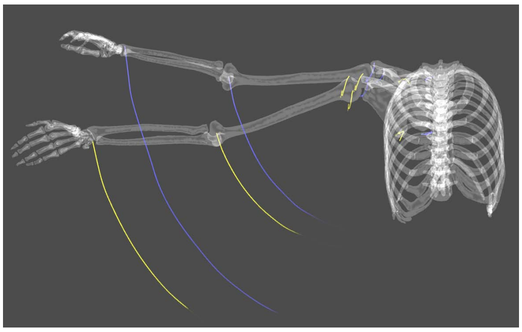


Figure 7: *Spline curve visualisation. This visualisation can be used to inspect a time window around a specific pose. An advantage of this visualisation method is that it shows how a subject reached for a specific area.*

abled, transforming the line drawings to take into account the disabled joint and its corresponding DOFs. This allows researchers to analyse what part of the functional range of motion can be ascribed to the range of motion of specific joints.

Axial rotation is an import kinematic parameter as it is often jeopardised in case of a pathology. Because each pose

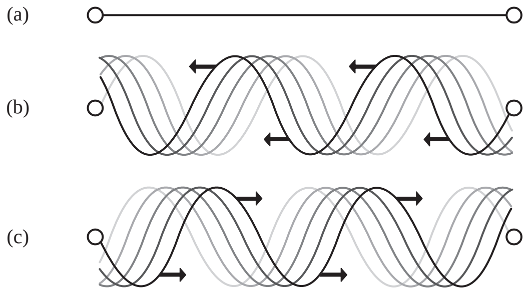


Figure 8: *Axial rotation visualisation. (a) Segments that consist of a single line, for example the upper arm, have axial rotation that is not visible using the standard line drawing. (b, c) Optionally these segments can be replaced by corkscrew lines, spiraling inward or outward depending on the sign and magnitude of the axial rotation. See Figure 9 for an example of this visualisation.*

is represented by a collection of simple lines, the basic visualisation is not capable of visualising the axial rotation of a segment. Optionally, the researcher can visualise axial rotation by replacing the line segments with corkscrew representations that rotate either inward or outward, depending on the sign and magnitude of the axial rotation (see Figure 8).

Alternatively, users can choose to visualise the poses as interpolated spline curves. Spline curves originate from a selectable set of joints, their length depending on the size of the adjustable time window. The benefit of spline curves is that they are time dependent and can therefore be used to analyse the time window around a specific pose. A disadvantage of this visualisation technique is that the view becomes cluttered when using large time windows for large quantities of data.

In the Pose View a skeleton surface model represents an individual pose when required. This includes the visualisation of newly acquired poses during recording and poses that have been selected in the parallel coordinates plot.

The Pose View includes a pose filter that uses the position of the hand of the skeleton surface model. By dragging the hand to different positions, recorded poses that do not come within a scalable sphere around the hand are occluded. In this way the filter can be used to visualise functional information, showing how a subject reached for a specific area. See Figure 9 for an example of this filter.

While the hand is dragged to different locations the skeleton surface model snaps to the closest pose that passes the filter. If none of the recorded poses pass the filter, a simple inverse kinematics model is used to determine the arm position for the new location of the hand. The inverse kinematics model determines the gradient of each of the DOFs and applies weighted rotations in accordance with these gradients. The individual DOFs are limited to the range of motion interval as determined from the motion recordings. The inverse kinematics model is only used for realtime visual feedback during interaction.

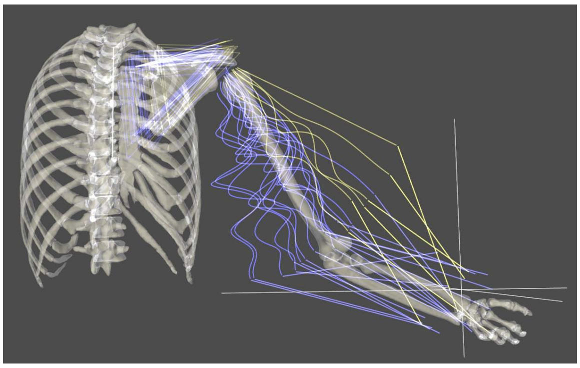


Figure 9: *The Pose View filter. The hand can be dragged to a position in space. This position is then used for an inverse query to determine how a subject reached for that position. Note that the subject of the yellow dataset reached for the point in a different manner compared to the subject of the blue dataset. Also notice that the blue lines of the upper arm are showing a larger amplitude, indicating that the axial rotation of the upper arm of this subject had a greater magnitude.*

3.5.3. Parallel Coordinates Plot

The parallel coordinates plot serves as a quantitative confirmation tool for motion patterns found in the DOF View and Pose View. Each recorded pose is represented by a single spline (see Figure 10). The view can be configured to accomodate the researcher's requirements, plotting any of the parameters in sequence. The selection and ordering of parameters depends on the research question and aspects of interest found in the DOF View or Pose View.

We adopted curved (cardinal) splines to distinguish multiple splines going through the same values, as was proposed by Graham et al. [GK03]. In combination with alpha blending this enables us to display a large number of poses without losing the focus on relationships between multiple DOFs of the kinematic data. Optionally, the user can switch to linear splines, as these may reveal linear relationships that are not visible when using cardinal splines.

The parallel coordinates view is linked to the other views. Selection of a specific spline will update the Pose View to show the selected pose. In turn, when any of the filters in the DOF View or Pose View are modified, the parallel coordinates view is updated.

3.5.4. 2D Plots

In addition to the above views, 2D plots of data values over time can be added (see Figure 10). Besides the informative

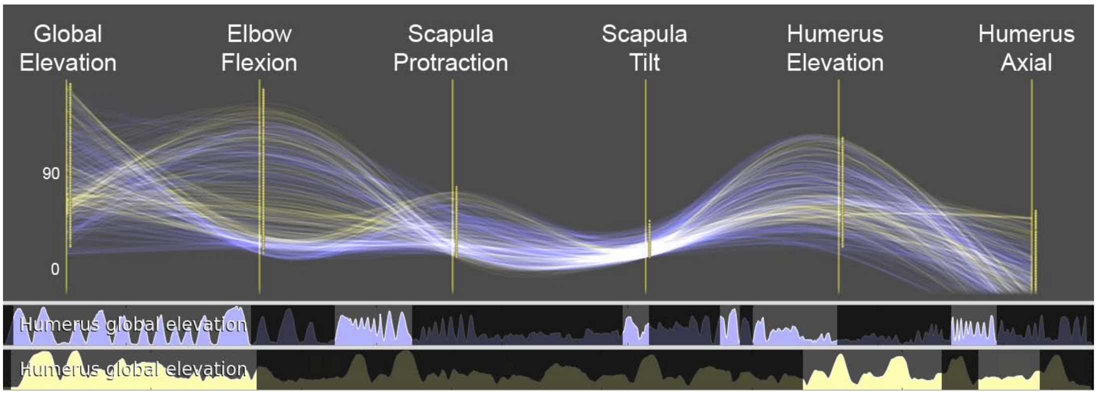


Figure 10: *Parallel coordinates plot for two sets of motion recordings. The plotted parameters can be customised. Below the parallel coordinates plot are two 2D plots of a specific parameter, in this case global elevation, over time for each dataset.*

aspect of these 2D plots, the researcher can use them as a timeline filter. Highlighting a range in one of the 2D plots causes the data outside of this range to be hidden. In practice this filter is frequently used complementary to a DOF filter. The latter filters a selection range of the DOFs, whereas the timeline filter allows selection of one of the intervals that passed the DOF filter.

3.5.5. Scatter Plots

Scatter plots can be generated by right-clicking between two axes of the parallel coordinates plot. All scatter plots are continuously updated, thereby only showing the recordings that have passed the active filters. Scatter plots are capable of revealing more complex relationships than possible with the parallel coordinates plot. The disadvantage of using scatter plots is that they can only show two parameters at once. As such, a scatter plot is comparable to angle-angle plots.

4. Evaluation

An evaluation experiment was performed with a patient who suffered a proximal humerus fracture injury. This is a complex fracture where the shoulder part of the upper arm shatters into multiple parts, each connected to a tendon of the different muscles of the rotator cuff, i.e. the muscles that provide shoulder stability. After the fracture occurred the shoulder was operated on to reconstruct the normal anatomy. The patient was seen eight months after trauma. In this time period the formerly fractured shoulder regained similar range of motion as compared to the healthy opposite side.

To demonstrate how our system can be employed to analyse the kinematics of these fractures we used the Flock of Birds system and instructed the patient to perform multiple elevation tasks in various manners. This included a crouched and extended attitude, forward elevation (flexion) and sideways elevation (abduction). Subsequently, the resulting motion recordings were analysed using our system.

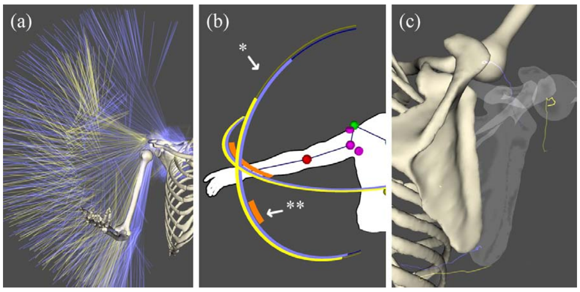


Figure 11: *Approach to answering the research questions, further explained in Section 4.*

No literature is available describing the kinematic changes for this specific type of injury. However, in normal shoulder kinematics the scapula (the shoulder blade) moves in unison with the humerus (the upper arm bone) during an elevation task. This is called the scapulohumeral rhythm. In healthy subjects this is a near linear relationship where for every degree of elevation the scapula upward rotation increases with ±0.5 degrees [EMK05]. With this experiment we wanted to assess whether this relationship still holds for the healed shoulder.

In summary, the research questions were:

1. Is there an impairment, and if so, where is it located?
2. Has the scapulohumeral rhythm of the formerly fractured side changed?

The steps followed to find the answers to the research questions are depicted in Figure 11. The Pose View (Figure 11a) demonstrates that the range of motion of the healthy side is larger than the range of motion of the formerly fractured side. The difference in range of motion is also evident from the DOF-view (Figure 11b, *-mark). Using the DOF filters we adjust the visible elevation interval (marked **)

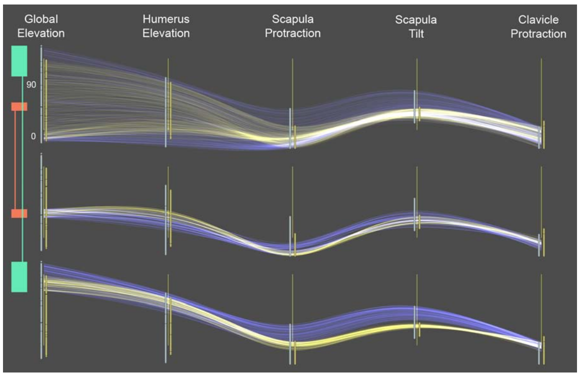


Figure 12: *Parallel coordinates plot of the mirrored formerly fractured shoulder (yellow) and the healthy shoulder (blue). The top subfigure shows the complete collection of splines, each one representing a recorded pose. The remaining subfigures show the same plot with different DOF filters for the global elevation parameter. The filters are visible on the left of the image. Notice the different values of scapula protraction and tilt at different global elevation angles, indicating that the scapula hardly compensates for the loss of humeral range of motion.*

and restrict our data to a specific elevation plane to allow for comparison of the two recordings. Subsequently, the different scapulohumeral rhytmn becomes visible, both by means of the surface models and by means of spline curves. To quantify the difference we inspect the parallel coordinates plot seen in Figure 12.

From this analysis we conclude that there is indeed an impairment. Interestingly, the deficiency does not just find its origins in the formerly fractured humerus, but also in the mobility of the shoulder blade. A possible reason for this can be the experience of pain or increased muscle tension.

Secondary to the above, the visualisation demonstrates that the scapula of the formerly fractured side does not move in unison with the humerus. Specifically, we conclude that the scapulothoracic rhythm of the right shoulder deviates from that of the left shoulder in that scapula protraction and tilt lag behind of humeral elevation.

A limitation we encountered during this experiment is that the limited accuracy of bony landmark registration may result in an offset for the coordinate systems or segment lengths. As was shown by Karduna et al. [KMMS01], this inaccuracy does not prevent analysis of motion patterns of individual datasets. However, when comparing multiple datasets as we did in this evaluation experiment, inaccuracy may lead to a relative offset in the coordinate systems used for kinematic analysis.

An involved orthopaedic surgeon later stated that he was impressed with the visualisation and speed of the system. His feedback was valuable for the continuation of this research.

5. Conclusions and Future Work

In this paper we have presented a novel visualisation system for the analysis of kinematic recordings for the upper extremity in combination with a new method of data sampling. The system currently supports six visualisation techniques that are collectively used to filter motion data and inspect relationships between the various DOFs. Although designed for the upper extremity, the presented techniques can be applied to other multi-joint chains.

The benefit of our visualisation system is that users can analyse kinematic recordings without predetermined hypotheses. It allows users to find interesting patterns that could otherwise only be found through a large number of angle-angle plots. Using the step-by-step approach described in our evaluation experiment the majority of kinematic research questions can be answered.

As was shown in the evaluation experiment, the visual analysis technique is effective for comparison of two recordings, bearing in mind that inaccuracy of the motion recordings may lead to incorrect representations. We are aware that these inaccuracies affect the kinematic analysis, but wish to emphasise that this problem also holds for conventional kinematic analysis. In addition, we have shown that our visualisation system is robust to these errors to a certain extent.

An interesting extension of the system would be to incorporate acquisition hints based on an automatic comparison of the acquired data with a collection of kinematic measurements. In this way the kinematic measurements themselves can zoom in on interesting characteristics, thereby not only relying on the assessments of the researcher.

An important message of this work is that kinematic behaviour requires a combination of visualisation and filtering techniques, as was demonstrated with our system. The modular design of our system allows for the implementation of additional filters and visualisation methods and raises the question whether this work should be taken one step further. It is conceivable that modular approaches commonly seen in image processing may be applicable for kinematic data, even though image data and kinematic data are of a very different nature. Future work includes the development of a data-flow network editor where filtering and visualisation modules can be connected to produce a specific kinematic visualisation.

Acknowledgements

This work was supported by a grant from the Dutch Arthritis Association (Reumafonds). We acknowledge Professor Roger Emery, Imperial College London, for his assistance in this research and Mr Peter Reilly, Imperial College London, for the formidable surgical result obtained.

References

[AMYBT04] Abdel-Malek K., Yang J., Brand R., Tanbour E.: Towards understanding the workspace of human limbs. *Ergonomics 47*, 13 (oktober 2004), 1386–405.

[BL91] Barraquand J., Latombe J.-C.: Robot Motion Planning: A Distributed Representation Approach. *The International Journal of Robotics Research 10*, 6 (december 1991), 628–649.

[CFSL07] Chen J., Forsberg A. S., Swartz S. M., Laidlaw D. H.: Interactive Multiple Scale Small Multiples. In *Proceedings of IEEE Visualization* (2007).

[CRM∗05] Côté J. N., Raymond D., Mathieu P. A., Feldman A. G., Levin M. F.: Differences in multi-joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. *Clinical biomechanics (Bristol, Avon) 20*, 6 (juli 2005), 581–90.

[De 97] De Groot J.: The variability of shoulder motions recorded by means of palpation. *Clinical Biomechanics 12*, 7-8 (1997), 461–472.

[Dem55] Dempster W. T.: Space Requirements of the Seated Operator, 1955.

[EMK05] Ebaugh D. D., McClure P. W., Karduna A. R.: Three-dimensional scapulothoracic motion during active and passive arm elevation. *Clinical Biomechanics 20*, 7 (2005), 700–709.

[GK03] Graham M., Kennedy J.: Using curves to enhance parallel coordinate visualisations. *Information Visualization, 2003. IV 2003. Proceedings. Seventh International Conference on* (2003).

[KBV∗06] Krekel P. R., Botha C. P., Valstar E. R., de Bruin P. W., Rozing P. M., Post F. H.: Interactive simulation and comparative visualisation of the bone-determined range of motion of the human shoulder. In *Proceedings of Simulation and Visualization* (2006), Schulze T., Horton G., Preim B., Schlechtweg S., (Eds.), SCS Publishing House Erlangen, pp. 275–288.

[KCJV09] Kontaxis A., Cutti A. G., Johnson G. R., Veeger H. E. J.: A framework for the definition of standardized protocols for measuring upper-extremity kinematics. *Clinical biomechanics (Bristol, Avon) 24*, 3 (2009), 246–53.

[KERC09] Keefe D., Ewert M., Ribarsky W., Chang R.: Interactive Coordinated Multiple-View Visualization of Biomechanical Motion Data. *viscenter.uncc.edu 15*, 6 (2009), 1383–1390.

[KMMS01] Karduna A. R., McClure P. W., Michener L. A., Sennett B.: Dynamic measurements of three-dimensional scapular kinematics: a validation study. *Journal of biomechanical engineering 123*, 2 (april 2001), 184–90.

[LK06] Lenarčič J., Klopčar N.: Positional kinematics of humanoid arms. *Robotica 24*, 1 (2006).

[LP90] Lozano-Pérez T.: Spatial planning: a configuration space approach. *Autonomous robot vehicles* (1990).

[Mac86] Mackinlay J. D.: Automating the Design of Graphical Presentations of Relational Information. *ACM Transactions on Graphics 5* (1986), 110–141.

[MCHS05] Manal K., Chang C.-C., Hamill J., Stanhope S. J.: A three-dimensional data visualization technique for reporting movement pattern deviations. *Journal of biomechanics 38*, 11 (2005), 2151–6.

[MS04] Manal K., Stanhope S. J.: A novel method for displaying gait and clinical movement analysis data. *Gait & posture 20*, 2 (2004), 222–6.

[RW99] Rowe G., Wright G.: The Delphi technique as a forecasting tool: issues and analysis. *International Journal of Forecasting 15*, 4 (1999), 353–375.

[VCR98] Van Sint Jan S. L., Clapworthy G. J., Rooze M.: Visualization of Combined Motions in Human Joints. *IEEE Computer Graphics and Applications 18*, 6 (1998).

[Whi06] Whittle M.: *Gait analysis: an introduction*, 4th ed. Butterworth-Heinemann Publishing, Oxford, 2006.

[WvV∗05] Wu G., van Der Helm F. C. T., Veeger H. E. J., Makhsous M., Van Roy P., Anglin C., Nagels J., Karduna A. R., McQuade K., Wang X., Al. E.: ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: shoulder, elbow, wrist and hand. *Journal of Biomech 38* (2005), 987–992.