A User-based Evaluation of Skeletal Animation Techniques in Graph Interaction

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Abstract

Skeletal animation is a concept that has been used in the areas of motion pictures and computer games to create realistic motion for the animation of articulated characters. Recent work (Merrick & Dwyer 2004, Murray et al. 2004) has applied skeletal animation techniques from inverse kinematics and dynamics to the field of graph interaction. The motivation for this paper is to evaluate the dynamics-based technique in terms of its ability to simulate the skeletal metaphor, and to evaluate the skeletal metaphor in terms of its usefulness for graph interaction. We conduct a user-based evaluation for this purpose. The results of which confirm the usefulness of both the dynamics-based technique and the skeletal metaphor in aiding the users understanding of a graph. *Keywords:* Graph Interaction, Skeletal Animation, User-based Evaluation

1 Introduction

A relational network or graph is commonly used to represent relations between objects. A graph consists of a set of nodes and edges where nodes represent objects and edges represent the relationship between objects.

Graph drawing takes the set of nodes and edges of a graph and assigns coordinates to the nodes so that they can be drawn. This produces a drawing that provides a geometric representation for a set of relational data. The aim of graph drawing is to produce a picture that allows the viewer to easily understand the information that is represented by a graph. A lot of research has been done in the area of graph drawing and this is discussed in more detail in the following section.

While a number of good graph drawing algorithms have been developed, there are always situations, particularly in 3D, where the layout provided is difficult to understand. In these situations it is desirable to have a mechanism to allow the viewer to modify both the graph layout and their view of this layout. Graph interaction techniques are designed to provide this mechanism.

Graph interaction allows the user to make changes to a graph drawing. The interaction technique used determines how the graph will respond to input from the user. Graph interaction is a field that aims to complement graph drawing by reducing the difficulty and time taken in understanding the information that is being represented by a graph. Effective interaction techniques have the potential to reduce the time that an analyst needs in order to navigate the presented information, and increase the amount of information that can be interpreted and understood.

One such way in which we can control how movements by the user will result in changes to the graph is through the use of a physical metaphor. The aim of a physical metaphor is to simulate a physical structure that the user is familiar with. This will result in changes that feel natural to the user. Any graph interaction technique should feel natural and intuitive, and a useful physical metaphor is able to provide this.

A physical metaphor that was recently introduced to graph interaction (Merrick & Dwyer 2004) is the skeletal structure. A skeleton in this case may be seen as a system of bones of fixed length connected by joints that may be rotated at any angle.

Using the skeletal structure for graph interaction has many advantages. Firstly, it is easily mapped onto a graph. The nodes of the graph are mapped to the joints of the skeleton and the edges of the graph are mapped to the bones of the skeleton. As the user drags a node, other nodes will move and joints will rotate. The interaction technique must ensure that edge-lengths remain constant.

The skeleton is also a structure that is manipulated by humans on a regular basis and therefore, it should feel natural and intuitive.

Graph interaction through skeletal animation was recently improved (Murray et al. 2004) with the introduction of a new technique forming a dynamics-based approach. However, while the improvements over the previous techniques were clearly demonstrated, a user-based evaluation was not performed. A usability study is a reliable way of measuring the usefulness of graph interaction techniques, as feedback from users is a strong indication of how easy and natural the system is to use. It also provides an indication of how enjoyable it is to use the system. Therefore, any method of graph interaction should be evaluated through a comprehensive user study to demonstrate how useful it is.

We have conducted such a user study that aims to provide answers to the following research questions:

1. Is the particle system useful for simulating skeletal animation in graph interaction?
2. Is the skeletal metaphor useful for graph interaction in the general case?

In answering these questions, the study aims to affirm or reject the following hypotheses:

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1. New techniques will have a positive effect on the simulation of the skeletal metaphor in graph interaction.
2. The use of the skeletal metaphor will have a positive effect on the user's ability to understand the graph structure

2 Background

Graphs have been used for a long time in conveying information and as a result of this a lot of research has been done in the area of graph drawing. Di Battista et al. provide a good review of this research (Di Battista et al. 1994, Di Battista et al. 1999).

Various aesthetic criteria have been discussed which attempt to measure the readability of a graph drawing by general optimisation goals (Esposito 1988). Examples of aesthetic criteria include minimisation of crossings, area, bends and maximisation of smallest angle and symmetries (Di Battista et al. 1994). In many cases, it is not possible to completely satisfy more than one aesthetic criteria simultaneously. It is also common to have an additional criterion requiring that certain constraints are satisfied (Dengler et al. 1993). Examples of possible constraints are keeping a certain vertex in a fixed position or keeping a group of vertices close together. An algorithm for producing a graph drawing is known as a layout algorithm. As a result of the large amount of research into graph drawing many layout algorithms have been developed that attempt to optimise specific aesthetic criteria.

The focus in this paper is on general undirected graphs drawn in three dimensions for which force-directed methods are often used. Force-directed methods define a system of forces acting on the vertices and edges. The graph drawing then evolves to a minimum energy state. Force-directed methods are relatively easy to implement, can easily be extended to three dimensions and the smooth evolution of the drawing helps to preserve the user's mental map (Gould & White 1986) as the layout changes.

Force-directed methods are widely used in the graph drawing field and many different force-directed algorithms exist. The spring embedder method (Eades 1984) represents edges as springs with unit natural length and non-connected vertices in the graph are connected by springs in the system with infinite natural length. As a result connected vertices are attracted to each other unless they are closer than unit length together. In that case they will repel each other. Non-connected vertices will repel each other. The system is then let go until a minimum energy state is reached.

Evaluation of the benefits provided by the aesthetic criteria on which graph drawing algorithms are based has produced mixed results (Batini et al. 1985, Ding & Mateti 1990, Purchase et al. 1997, Purchase et al. 2001). In any automated graph drawing system there will be situations where the initial graph drawing provided is not easy to understand. Also, many automated graph drawing systems provide an analyst with only one drawing of a graph. If the viewer is unable to understand the graph based on this one drawing, they will have no further avenue in which to comprehend the information. By providing the user with a mechanism for changing the layout of the graph we facilitate a potential increase in the users understanding of the graph. Studies into the effectiveness of graph interaction techniques support this (Herman et al. 2000). The limitations of current graph drawing techniques and the need for interaction is discussed further in (Merrick & Dwyer 2004, Murray et al. 2004).

Graph interaction techniques determine how the graph reacts to actions by the user. The main problem in graph interaction is providing a mechanism that will ensure that the graph becomes and remains understandable as the user navigates the graph. It is desirable that the graph will react in a way that is natural and intuitive (Merrick & Dwyer 2004). Graph interaction techniques attempt to provide solutions for this problem.

A number of techniques have been used to aid the interaction of a user with a graph. Techniques that are used to control the view of a fixed graph drawing include the operations of rotation, scaling and translation. In this paper we will be focusing on methods that allow the user control over the positions of the nodes themselves. These methods give the user greater control over how the graph is drawn.

While we want to give the user a degree of freedom in navigating the graph, we also want to maintain some control over the layout of the graph to ensure certain properties remain unchanged. Placing such constraints over the control of the graph will ensure that we continually provide an aesthetically pleasing graph drawing and this will assist the user in finding an understandable layout. In addition it may reduce the time taken for the user to achieve such a layout.

The simplest way of providing graph interaction is to use an adaptive graph drawing algorithm. An adaptive graph drawing algorithm produces a drawing that is dependent upon the initial geometric properties given to the graph. These types of algorithms effectively take a graph drawing and their aim is to improve upon it. Adaptive graph drawing algorithms are useful for graph interaction tasks as they are more likely to preserve the user's mental map. The speed requirements of an algorithm used for graph interaction is higher than that of general graph drawing. Algorithms developed with graph interaction in mind (Bruβ & Frick 1996) are designed to be very fast.

One method used in graph interaction involves placing a physical metaphor on the structure of the graph such that the graph responds to movements of nodes in a way corresponding to the physical metaphor. A common physical metaphor in undirected graph drawing is the force-directed paradigm and this idea is easily extended to graph interaction as force-directed algorithms are adaptive. Forces are recalculated as the user moves a node and the position of the nodes are updated accordingly.

Skeletal animation is a concept that is commonly used in the areas of computer games and motion pictures. As a result a large number of techniques have been developed that control the movement of a skeleton in a way that is designed to appear natural to the viewer.

Recent work has applied the skeleton as a physical metaphor to the field of graph interaction (Merrick & Dwyer 2004). By applying skeletal constraints on a graph we can provide a physical metaphor that feels natural to the user and the time taken in navigating the graph is reduced.

The focus of the previous work was on inverse kinematic techniques. Inverse kinematic methods move a joint to a desired position while controlling the movement of several other joints and taking into account positions of fixed joints, bone lengths and joint angles. These techniques are often used in the area of robotics.

While inverse kinematics techniques operate on the geometry of articulated structures, dynamics models all interactions with the system as forces acting upon rigid and articulated bodies. Inverse kinematics techniques have been useful for robotics, and as a result, it has been the topic of the majority of research in skeletal animation. However, there has also been some development of dynamics-based techniques, a lot of which has been driven by the need for skeletal animation techniques in computer games, where the main goals are believability and speed of execution. In order to achieve believability, dynamics-based techniques focus on emulating motion as seen in real environments. These methods are less focused on goal directed motion. These methods use an iterative approach where, at each iteration, the forces upon the particles that make up a body, are summed in order to determine their following positions. This process is repeated in order to generate motion.

The simulation of a skeleton was improved with the introduction of a dynamics-based technique (Murray et al. 2004). The technique was adapted from the physics system described by Jakobsen (2001) . The new technique improved upon the previous work in terms of simulation of the skeletal metaphor, speed of execution, smoothness of motion and the addition of angular constraints for increased realism.

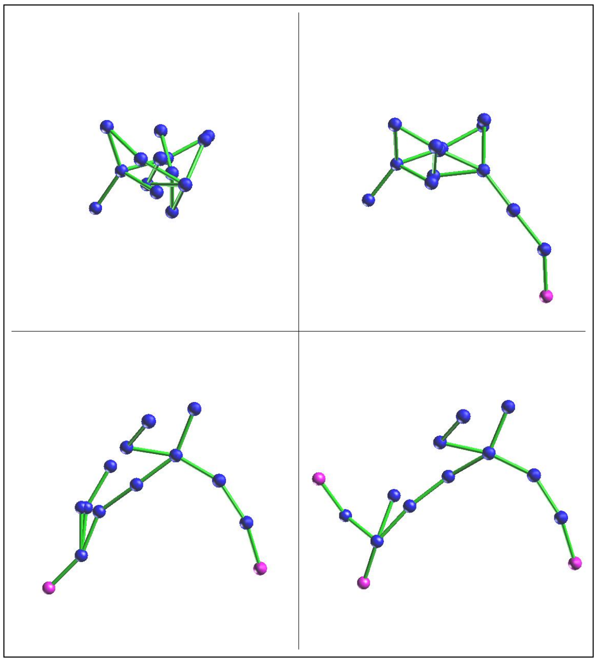

Figure 1: Dragging nodes in the skeletal interaction system. Constraints are maintained as the nodes are moved.

In that work, the author implemented the physics system into a three dimensional graph interaction environment. We use this implementation for our user study. The graph was modelled as an articulated body with joints representing nodes and bones representing edges. The implementation allowed the user to drag the nodes of the graph around and the graph responded according to the underlying physics engine. As a node is dragged around, the edge length constraints are satisfied by a constraint solver. This ensures that as a node is dragged surrounding nodes will move closer or further away from the dragged nodes in order to maintain the constraint. This creates a natural feel in the system as the edges remain at constant length similarly to the bones of a skeleton. An example of the motion generated by the system can be seen in Figure 1.

The calculation of a nodes position at each integration step can be performed in linear time. This is because each node must be visited once. In order to satisfy the edge-length constraint, each edge must be visited once. Therefore the standard skeletal technique is linear in the larger of the number of nodes or edges.

In any graph interaction environment it is useful for the user to be able to fix nodes so that they will remain in the same location. The user can select nodes to be fixed or can unfix nodes at any time. This was implemented by adding the constraint that the subset of nodes that is fixed cannot move. This is a hard constraint and is given priority over the other constraints so that the fixed nodes will not move from the set position at all. This introduces a problem in ensuring that the edge length constraints are satisfied, for example, if two nodes connected by a stick are fixed. If the user drags one of these nodes away the edge will increase in length and the constraint will be violated as the system cannot move either node in an attempt to satisfy the constraint.

To remedy this problem the author placed restrictions on how the user can drag nodes around. Movements of nodes that will violate an edge length constraint significantly are not allowed. This maintains some freedom of control for the user while still providing the natural feel of the skeletal structure. A threshold that measures the sum of violations across the entire graph is used to determine if the extent of a violation is acceptable. Once the maximum threshold is reached, movement will be limited to actions that reduce or maintain the current extent of violations. After reducing the extent of the violations, the user will then once again be able to make movements freely. This provides restrictions on the movement that more closely resemble a physical structure as is the nature of the skeleton. As a result, it is expected to provide a more natural feel and be more effective at maintaining the skeletal structure. There is a mechanism for navigating the graph with or without the threshold restrictions.

Visual cues where also provided to indicate where and by how much violations are occurring. A significant edge length violation will result in a change in colour of the edge from green to red. Also, the width of the edge will decrease if the edge is stretched and will increase if the edge is compressed. The visual cue of using blue for unfixed nodes and highlighting fixed nodes in pink is also provided to ensure the user is aware of the subset of fixed nodes.

The original definition of a skeleton does not specify any angular constraints. However, in terms of graph navigation, there is a possible benefit of implementing angular constraints as it would keep nodes from getting too close together. The author implemented angular constraints in the system by applying forces between unconnected nodes. Unconnected nodes whose distance is less than a threshold are repelled from each other. The forces on each node are summed in a way similar to force-directed methods and nodes are moved in the direction of the force. The calculation of forces and movement of nodes is performed within the constraint satisfaction loop. While this is not always an accurate way of providing angular constraints, it is simple and provides a realistic feel most of the time. This method not only adds realism to the skeletal structure, it also provides aesthetic benefits. It prevents unconnected nodes from getting too close together and this results in good angular resolution. Edges emanating from a node will spread evenly around that node. The skeletal technique with angular constraints has the additional operation of calculating the forces on each node. Each node must determine the force exerted upon it by possibly every other node. Therefore the time complexity is quadratic in the number of nodes. This is the main disadvantage of the method with angular constraints over the standard skeletal method.

3 Description of the Process and Survey Questions

Participants of the user study used the implementation of the particle system (Murray et al. 2004) to perform graph interaction tasks. They were asked to answer survey questions based on their experience with the system. The survey questions are described in this section. We had 16 participants take part in our user study. They were postgraduate and Honours students in the field of computer science.

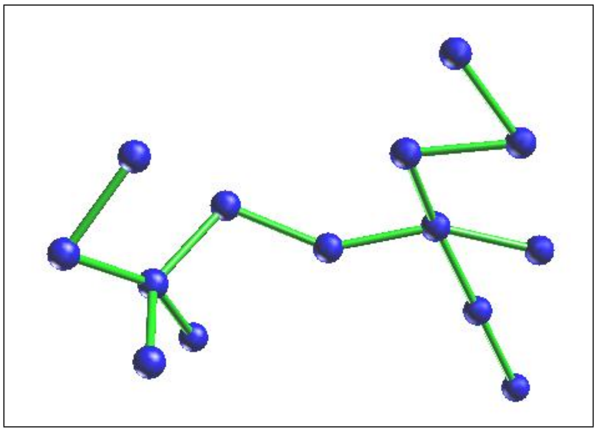

Figure 2: The graph used for part 1 of the user study.

Part 1 of the survey involved using the system on the graph given in Figure 2 using the particle system both with and without the threshold. As described in (Murray et al. 2004) the threshold restricts the movement of the user in order to better maintain the skeletal constraints. The threshold used for the study was determined experimentally. We used a threshold that provided a balance between restricting the user's movements too much and allowing excessive violation of constraints.

The purpose of part 1 of the survey was to evaluate the particle system in terms of its ability to simulate the skeletal metaphor. The aim of this part is to answer research question 1 while giving a small insight into question 2. This part was also designed to compare the particle system using the threshold to the particle system not using the threshold.

The participants of the study were asked to provide a rating for each technique on an integer scale of 1 (lowest) to 5 (highest), for the first four questions. For the remaining questions in this part, the participants were asked to give a written response explaining their answer. The questions were:

A How well does the system preserve the structure of the skeleton? (Structure is preserved when the lengths of bones are at their original length)

B When dragging around a node, did the bones react in the way you expected (How intuitive is the system)?

C While moving a node was it easy to maintain your understanding of the structure of the graph?

D Was the system fun to use?

E Which aspect of each system did you like the most, Why?

F Which aspect of each system did you like the least, Why?

G Based on your experience with the two systems what do you consider to be most important, maintaining the skeletal structure or allowing freedom of movement? Explain.

H Do you have any further comments to make on any aspect of these systems or this section?

For questions A-D the participants were advised to give ratings in such a way that the techniques could be measured individually against the scale as well as comparatively. There was also space for additional comments after each question so that the user could further explain their choice if desired.

Question A is aimed at measuring and comparing the ability of each technique to satisfy the bone-length constraints of the skeleton. This is the most important factor in terms of measuring a techniques ability to simulate a skeleton. It is the nature of the skeleton that bone-lengths remain constant. If this is not the case then it could be argued that the system is only loosely simulating a skeleton. The visual cues provided in our system mean that the user will always know if the bone-length constraints are satisfied. This will ensure that the answers provided by participants in this question will be an accurate representation of the level of constraint satisfaction.

Question B tries to identify which technique users find most natural or intuitive. Due to the fact that a skeleton is a natural structure that humans are used to manipulating, it is expected that a system that simulates the skeleton effectively would be natural and intuitive. If the system is found not to be intuitive it could mean that it is not simulating the skeleton very well. However, it could also mean that the skeletal metaphor is not as natural and intuitive as expected when applied to graph interaction.

Question C is present to measure the success of each algorithm in preserving the user's mental map. The mental map is likely to be maintained if only small, intuitive changes are made. If large, drastic changes are made then the user will be unable to identify how the current drawing relates to previous drawings and the benefits of interaction are reduced. A system that simulates the skeleton well is expected to maintain the mental map as changes are restricted to maintain similar aesthetic properties.

Question D has been included as an informal way to ascertain the algorithm of general preference to the participants and also to determine how enjoyable each technique is to use. Questions E & F have been included to record what the users consider to be the strengths and weaknesses of the two methods. The purpose of Question G is to determine whether restrictions placed upon the movement of the graph in order to better satisfy the skeletal constraints, helps or hinders their ability to understand the graph structure. Question H is for any extra comments the participant may have.

Part 2 of the survey involved using the system on the graph given in figure 3 using the particle system, a force-directed technique and the particle system with angular constraints. While part 1 was designed to give some insight into the usefulness of the skeletal metaphor, only by comparing the particle system with a non-skeletal technique can we completely identify it's strengths and weaknesses. Evaluating the new skeletal technique against a traditional non-skeletal technique is the purpose of part 2 of the survey. The particle system simulates the skeleton while the force-based method is non-skeletal. The particle system with angular constraints is a skeletal animation technique but also has force-based elements. These techniques will be evaluated in terms of the users understanding of the graph structure. The aim of this part is to answer research question 2.

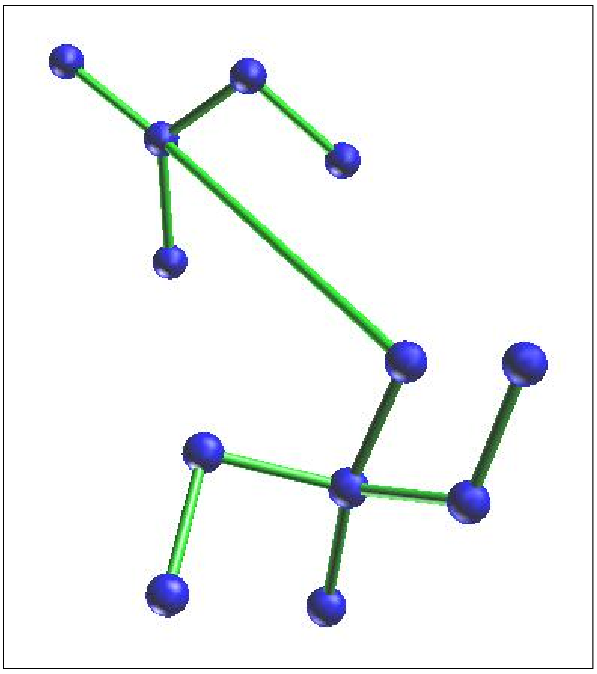

Figure 3: The graph used for part 2 of the user study.

Once again, the participants of the study were asked to provide a rating for each technique on a scale of 1 to 5, for the first four questions. Space for additional comments was again provided. The remaining questions again required a written response. The questions were:

A How easy was it to obtain a picture in which you could easily understand the structure of the graph?

B While moving the structure around, did the graph react in the way you expected (How intuitive is the system)?

C While moving a node was it easy to maintain your understanding of the structure of the graph?

D Was the system fun to use?

E Which aspect of each system did you like the most, Why?

F Which aspect of each system did you like the least, Why?

G Do you have any further comments to make on any aspect of these systems or this section?

Question A attempts to capture a general notion of the skeletal metaphor's effect on a user's ability to manipulate the graph into a readable form. The main aim of graph interaction is to allow the user to easily produce a drawing that they can understand. Therefore, the performance of a technique in this question give a strong indication of how useful it is for interaction tasks.

The remaining questions have a similar purpose to those in part 1, this time comparing skeletal and non-skeletal techniques.

4 Results & Discussion

Part 1 - Comparison of Skeletal Techniques

The results from part 1 of the user study are shown as a column graph in Figure 4. To obtain the value for each method and question we took the average of the responses provided. The confidence intervals were calculated with a 95% confidence level. From the graph we can easily see the performance of each method against the scale and we can also easily compare the methods.

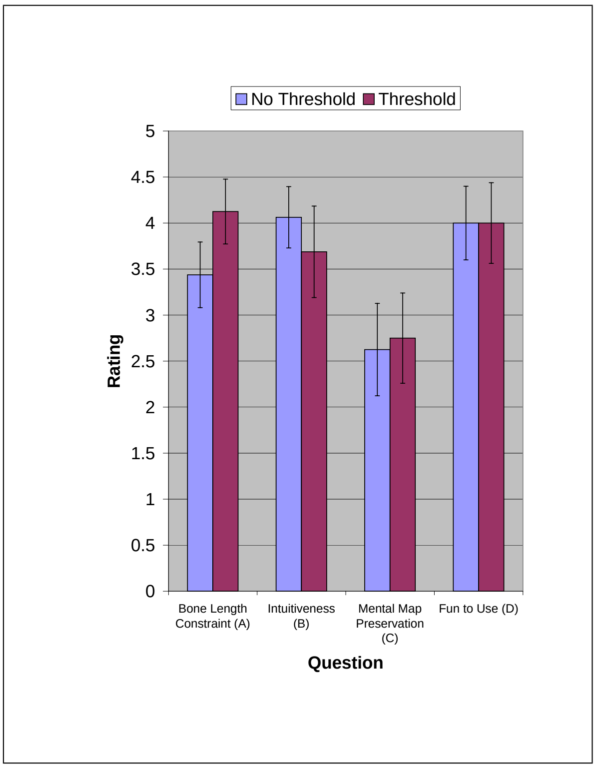

Figure 4: The results for part 1 of the user study.

From the results in question A it can be seen that the threshold method is more effective at preserving edge lengths than the non-threshold method. This strong trend towards the threshold method as a better preserver of edge-lengths was to be expected, as the non-threshold method allows the user total freedom in stretching bones. However, the scores were still towards the high end of the scale, indicating that edge lengths were well preserved. This is because violations will only occur in cases were the fixed nodes are chosen such that it is impossible to satisfy edge-lengths. In normal cases, all constraints will be satisfied. As the threshold method prevents some cases where it is impossible to satisfy edge constraints, it is better at preserving edges lengths. Some participants did not indicate any difference between the threshold and non-threshold methods. This may be because they did not create or attempt to create configurations in which the violation threshold would be exceeded. The threshold chosen still allowed some violations. Perhaps with a lower threshold, the difference between the methods would have been more obvious. However, this would have limited the usefulness of the method, as movement would feel too restrictive. In hindsight, it would have been beneficial to construct more study cases with a wider variety of circumstances. Based on the results achieved, it seems fair to claim that both methods are very effective in satisfying the skeletal constraints and therefore in simulating the skeletal metaphor.

The results in question B indicate that both methods are highly intuitive and feel natural to use. This shows that these methods are effective in aiding the understanding of the graph and also shows that the skeletal metaphor is useful for graph interaction.

From the results in Question C cause some concern as both methods are somewhat low on the scale. This indicates that too many changes could be occurring to the graph as nodes are dragged around making it difficult to see how the current state of the graph relates to previous drawings. While the ability of the skeletal metaphor to preserve the mental map is not terrible, it does appear to be its weakest aspect.

As can be seen from the results for Question D, both techniques are quite fun to use. The results also indicate that the users did not have a preference for either system.

The remaining questions produced a wide range of comments. Maintaining the skeletal structure was considered by the majority of the participants to be the more important factor in aiding understanding of the graph. Many argued that by maintaining the skeletal structure we are more likely to produce an aesthetically pleasing drawing, therefore making it easier to understand the graph structure. Also, if the lengths of edges were representative of edge weights specific to the graph, this is especially important for understanding the graph structure. Some also suggested that when the graph was released from a highly stretched state by releasing nodes, the graph would change drastically. This would result in a loss of the users mental map. If we maintain the skeletal structure these highly stretched states are less likely to occur. Also, highly stretched states are more likely to have poor aesthetic properties. Some commented that the threshold added more realism to the skeleton structure as it would not be possible to stretch an actual skeleton.

Some of the participants preferred freedom of movement as a more important aspect. This allows them to place the graph in any possible configuration and by unfixing nodes, they can also ensure that the skeletal structure is satisfied. One user commented that relaxing the constraints is beneficial in an interactive environment. This makes sense, as for a single graph drawing we do want all constraints to be satisfied. However, in an interactive situation, it seems acceptable to temporarily allow some violations while a configuration is being formed. Once we have achieved a configuration which we can understand, satisfying any small violations will increase the aesthetics of the drawing and increase our understanding of the graph even further. Also, for graph drawings subject to edge length constraints, there may be no embedding that satisfies the constraints (Borcea & Streinu 2002). So we must allow some violation of constraints or we will limit the areas in which our techniques will be useful.

Based on these comments, we conclude that maintaining the skeletal structure is the most important characteristic as it helps to provide an aesthetically pleasing drawing that is easy to understand. However, we also believe that the skeletal structure can be maintained in an environment allowing complete freedom of movement, as long as the user makes an attempt to avoid configurations that highly stretch the graph, by paying attention to the visual cues and also keeping the subset of fixed nodes fairly minimal. Using this technique with that mind-set would allow the user to configure the graph in any possible way while maintaining the skeletal structure and therefore continually achieving an aesthetically pleasing drawing, that feels realistic and natural, therefore increasing the users understanding of the graph.

Both systems have shown to be useful for simulating the skeletal metaphor. Whether this aids the users understanding of the graph will be evaluated further in part 2.

One respondent commented that the structure responded quickly to user input in both techniques. This further supports our claim that the particle system is fast and helps to provide smooth, natural motion.

Part 2 - Comparison of Skeletal and Non-Skeletal Techniques

The results from part 2 of the user study are shown as a column graph in Figure 5. To obtain the value for each method and question we took the average of the responses provided. The confidence intervals were calculated with a 95% confidence level. From the graph we can easily see the performance of each method against the scale and we can also easily compare the methods.

The first thing that we notice from the graph is that the skeletal technique with angular constraints outperforms the other techniques in all questions. This indicates that the skeletal technique with angular constraints is the best at aiding a user's understanding of a graph.

For question A, the skeletal and force-directed techniques both have high enough ratings to indicate that they are useful for quickly and easily obtaining a readable graph. The rating of the skeletal technique with angular constraints is very high showing that it is extremely useful for this purpose.

The results for question B indicate that the skeletal technique with angular constraints is the most intuitive method. The natural motion provided by the skeletal metaphor combined with angular constraints provides an intuitive system because people regularly manipulate a skeletal structure. However, the skeletal structure without angular constraints is not necessarily more intuitive than the force-directed algorithm. This shows that the angular constraints are are very useful for ensuring that the system is intuitive. This is due to the fact that it provides added realism as the movement of joints in a normal skeleton have restrictions on the range of movement.

In question C all methods are shown to be fairly effective in preserving the users mental map.

The users also have a preference for the angular constraints method as shown in question D. They are more likely to enjoy using the system if it helps them to understand the graph.

The remainder of the questions requiring descriptive answers further supported the results obtained previously but failed to provide much further insight into the usefulness of each technique.

In summary, the results show that the skeletal technique with angular constraints is better at assisting a user to understand the graph structure than the non-skeletal technique. Adding angular constraints to the skeletal metaphor has the effect of providing good angular resolution which increases its usefulness significantly. It is also shown that there is no significant difference between the standard skeletal technique and the force-directed method. Therefore, we propose the following revised version of the definition of a skeleton:

A skeleton is a set of joints (J) and a set of bones (B). Each joint $j \in J$ is connected by a set of bones $B_j \subseteq B$ to set of joints $j_{ADJ} \subseteq J, |j_{ADJ}| > 0$.

There exist constraints on the skeleton that should be preserved:

- The length l_b of each bone $b \in B$ should not change.

- Given a set of joints $F \subseteq J$, termed the fixed point set, each joint $j \in F$ should remain at its initial location in Euclidean space.

- For each pair of joints $j_i, j_j \in J$ not connected by a bone $b \in B$, the Euclidean distance between j_i and j_j must remain greater than some threshold t.

The skeletal method with angular constraints does have the disadvantage that the extra work in enforcing the angular constraints makes this method a bit slower.

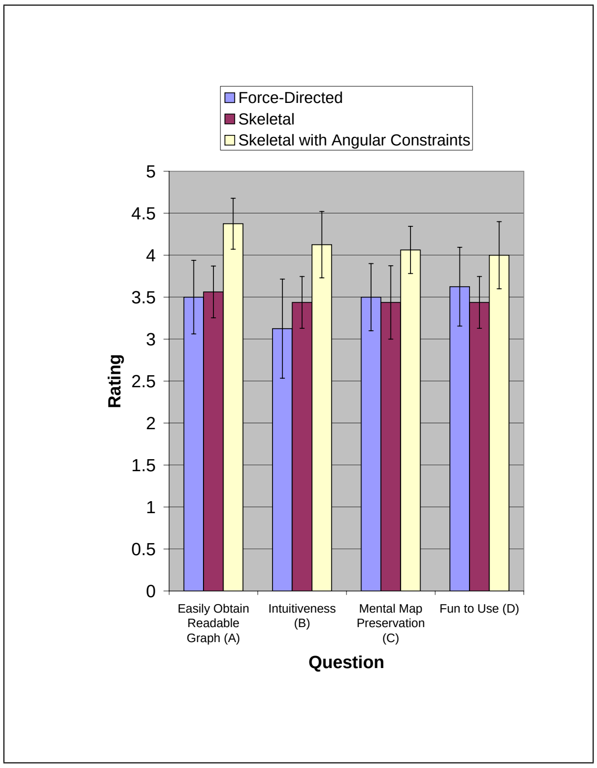

Figure 5: The results for part 2 of the user study.

Our results show that the skeletal metaphor is useful for graph interaction as it significantly helps the user to comprehend the graph.

From the results of our study we were able to confirm our hypotheses that new techniques will have a positive effect on the simulation of the skeletal metaphor and that the use of the skeletal metaphor will have a positive effect on the user's ability to understand the graph structure.

5 Conclusion

Through a usability study, we have evaluated the particle system in terms of its ability to simulate the skeletal metaphor. We have also evaluated the skeletal metaphor in terms of how useful it is for graph interaction. The results shows that the physics system has had a positive effect on the simulation of the skeletal metaphor and that the skeletal metaphor has has a positive effect on the user's ability to understand the graph structure.

This work provides the most convincing evidence to date that skeletal metaphor has several advantages over other types of interaction with graph visualisations. The initial work in this area (Merrick & Dwyer 2004) produced a user-based evaluation of the usefulness of the skeletal metaphor that was inconclusive due to the limited scope of the survey undertaken. The follow-up work (Murray et al. 2004) introduced a new technique that clearly improved upon the previous work but did not describe a user-based evaluation. We have demonstrated its usefulness through a comprehensive user study into the benefits of the skeletal metaphor and the different methods used. The results clearly show that the dynamics-based skeletal technique with angular constraints is much more effective at providing a mechanism for which the user can easily understand the graph. The comprehensive user study that we have undertaken also produces solid evidence of the usefulness of the skeletal metaphor.

We have also added angular constraints to the definition of the skeletal metaphor to further improve its utility. Our user study shows that this is necessary in order to obtain advantages over the non-skeletal technique.

The only method of interaction with skeletal graph interaction systems (Merrick & Dwyer 2004, Murray et al. 2004) to date is through the use of a standard two dimensional mouse. Other devices for interaction with three dimensional displays could provide a more natural interface between the user and the system, complementing the skeletal metaphor. In particular, haptic interaction devices not only provide a method for interaction in three dimensions but use force feedback techniques to give the user an actual physical feel of what they are interacting with. This would allow for the addition of further physical properties to the graph. The benefits of haptic devices have been explored (Hinckley 1996) and these devices have been shown to be quite useful for a range of applications. It remains to be determined, when using a graph interaction system utilising the skeletal metaphor, what additional benefits would be provided by using haptic devices. One of many possible benefits would be to allow the user to more easily determine when a threshold has been reached through the use of force-feedback.

The work of Ware and Franck has shown (Ware & Franck 1994) that many of the benefits of three dimensional visualisations are further realised when 3D display devices such as a stereoscopic, hand-tracked 3D display are used. The use of the skeleton metaphor with such devices is therefore likely to see even more benefits.

Our evaluation of the different techniques used gave us a strong indication of how useful the skeletal metaphor is for general graphs. However, graph drawing and interaction techniques designed solely for general graphs are often not useful once they are applied to domain-specific graphs (Purchase et al. 2001). Many domains consist of graphs that are much larger than those used for the experiment. The use of larger graphs will give a better idea of the scalability of the techniques. A faster method of calculating angular constraints will most likely be necessary but many faster methods for calculating forces between nodes such as Fade (Quiqley & Eades 2000) exist and would easily be implemented. The evaluation of graph interaction techniques in specific domains would give greater understanding by having expert analysts complete specific graph interaction tasks with labelled graphs representing real data. With specific tasks identified, it would also be better if quantitative measurements of the user performance were taken in addition to the subjective user comments. There are many domains in which these techniques could be evaluated. The skeletal metaphor is potentially useful in any application where it is crucial to visualize structural information as graphs. Further evaluation of the use of the skeletal metaphor in specific domains remains an area for future work.

Another possibility would be to use additional data associated with the graph to determine physical aspects of the graph. Some parameters that could depend on the input graph could be edge thickness, length and stretching threshold. These factors would provide a physical structure that more closely resembles the graph data. It remains to be seen whether this would increase the user's understanding of the graph but it's an area worth exploring.

In our system it was possible for nodes and edges to pass through each other. Collision detection involves determining if two objects intersect each other. Adding collision detection to a skeletal graph interaction system would provide further realism, as it could be used to prevent nodes and edges from intersecting. Collisions could also be felt by the user through a haptic interface. This may increase the ability of the user to understand the graph, and is therefore an area worth investigating.

This paper has not only contributed to the field of graph interaction but have also opened up many possibilities for future work in this area. Such research is likely to provide an important contribution in the fields of both graph visualisation and human computer interaction in the future.

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