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We started class by looking at a couple of recent papers that use machine learning to tackle the problems of rigging and skinning.

Xu, Zhan, Yang Zhou, Evangelos Kalogerakis, Chris Landreth, and Karan Singh. "RigNet: neural rigging for articulated characters." *ACM Transactions on Graphics (TOG)* 39, no. 4 (2020): 58-1.
https://zhan-xu.github.io/rig-net/

Liu, Lijuan, Youyi Zheng, Di Tang, Yi Yuan, Changjie Fan, and Kun Zhou. "Neuroskinning: Automatic skin binding for production characters with deep graph networks." ACM Transactions on Graphics (TOG) 38, no. 4 (2019): 1-12.
https://dl.acm.org/doi/abs/10.1145/3306346.3322969
http://kunzhou.net/

We then had a look at direct methods for skinning, which are widely used in production, specifically Linear Blend Skinning (LBS) and Dual Quaternion Skinning (DQS). As resources to discuss these techniques, I used the following papers:

This SIGGRAPH 2014 course contains a great deal of useful information.

Alec Jacobson, Zhigang Deng, Ladislav Kavan, J. P. Lewis.
Skinning: Real-time Shape Deformation
SIGGRAPH Course, 2014.

Linear blend skinning (LBS) and its problems are described in the first section of the SIGGRAPH course notes. In particular, there is a nice description of the candy wrapper effect.

Much research has focused on maintaining the speed and ease of use of LBS and removing the artifacts. We talked about this paper, which uses dual quaternion blending to remove twisting artifacts:

Kavan, Ladislav, Steven Collins, Jiří Žára, and Carol O'Sullivan. "Geometric skinning with approximate dual quaternion blending." *ACM Transactions on Graphics (TOG)* 27, no. 4 (2008): 105.
http://dl.acm.org/citation.cfm?id=1409627
https://www.youtube.com/watch?v=LUOJccOZfWQ

If you are interested in learning more about dual quaternions, this paper is one of many overview / tutorials which explain the idea:

Leclercq, Guillaume, Philippe Lefèvre, and Gunnar Blohm. "3D kinematics using dual quaternions: theory and applications in neuroscience." Frontiers in behavioral neuroscience 7 (2013): 7.
https://www.frontiersin.org/articles/10.3389/fnbeh.2013.00007/full

Here are a couple of other useful references. The first explains how linear interpolation for quaternions differs from proper spherical interpolation.
http://number-none.com/product/Hacking%20Quaternions/

The second gives a little bit of an introduction to what dual quaternions are and why they are useful (e.g., see the section on Dual Quaternion as a Rigid Transform).
http://simonstechblog.blogspot.com/2011/11/dual-quaternion.html

This paper introducing the idea of differential blending (breaking up large rotations into collections of small ones), which works well even for very large twists and deformations, such as might be needed for cartoon effects. Remember the twisting cow I showed in class? This is the paper that describes how they kept track of the amount of twist.

Öztireli, A. Cengiz, Ilya Baran, Tiberiu Popa, Boris Dalstein, Robert W. Sumner, and Markus Gross. "Differential blending for expressive sketch-based posing." In *Proceedings of the 12th ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, pp. 155-164. ACM, 2013.
https://graphics.ethz.ch/publications/papers/paperOzt13.php

I mentioned in class that skinning research can be divided into three categories: physics based, example based, and geometry based. Geometry based are just the direct methods we have seen already, such as LBS and DQS.

We talked briefly about pose-space deformation (an example-based approach) and caging (another geometry-based approach). Here are the references:

Lewis, John P., Matt Cordner, and Nickson Fong. "Pose space deformation: a unified approach to shape interpolation and skeleton-driven deformation." In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pp. 165-172. 2000.
https://dl.acm.org/doi/10.1145/344779.344862
https://www.youtube.com/watch?v=XPxRftplwJM

Corda, Fabrizio, Jean-Marc Thiery, Marco Livesu, Enrico Puppo, Tamy Boubekeur, and Riccardo Scateni. "Real-Time Deformation with Coupled Cages and Skeletons." In *Computer Graphics Forum*, vol. 39, no. 6, pp. 19-32. 2020. http://pers.ge.imati.cnr.it/livesu/papers/CTLPBS20/CTLPBS20.html

Here are two examples of physics-based approaches. Physics based approaches are designed to capture effects such as skin jiggle that result from dynamic motions and impacts that cannot be captured from static pose alone.

Kim, Meekyoung, Gerard Pons-Moll, Sergi Pujades, Seungbae Bang, Jinwook Kim, Michael J. Black, and Sung-Hee Lee. "Data-driven physics for human soft tissue animation." ACM Transactions on Graphics (TOG) 36, no. 4 (2017): 1-12. https://ps.is.tuebingen.mpg.de/publications/meekyoung-siggraph

Mukai, Tomohiko, and Shigeru Kuriyama. "Efficient dynamic skinning with low-rank helper bone controllers." ACM Transactions on Graphics (TOG) 35, no. 4 (2016): 1-11. https://mukai-lab.org/publications/siggraph2016/

Here are two additional papers that use example-based techniques. Remember that example based techniques are based on the principle that the correct weights may not be constant over the pose space and the way to get good results is to fix up and store numerous artist generated (or captured) examples at different poses and blend between them.

Le, Binh Huy, and Zhigang Deng. "Robust and accurate skeletal rigging from mesh sequences." ACM Transactions on Graphics (TOG) 33, no. 4 (2014): 1-10. http://graphics.cs.uh.edu/ble/papers/2014s-ske/

Loper, Matthew, Naureen Mahmood, Javier Romero, Gerard Pons-Moll, and Michael J. Black. "SMPL: A skinned multi-person linear model." ACM transactions on graphics (TOG) 34, no. 6 (2015): 1-16. https://smpl.is.tue.mpg.de/

It is also interesting to consider whether it is important to model the underlying anatomy to obtain good skinning results. This paper shows an example of the idea:

Ali-Hamadi, Dicko, Tiantian Liu, Benjamin Gilles, Ladislav Kavan, François Faure, Olivier Palombi, and Marie-Paule Cani. "Anatomy transfer." ACM Transactions on Graphics (TOG) 32, no. 6 (2013): 1-8. https://dl.acm.org/doi/abs/10.1145/2508363.2508415