Strand-based Simulation of Tendinous Systems

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INTRODUCTION

One of the challenges in computational biomechanics is simulation of the musculoskeletal dynamics with tendons and complex routing constraints. Tendons move freely in the axial direction, even in highly constraining configurations. Moreover, tendons that wrap around bones can exert forces on the bones at not only the origin and insertion, but also at intermediate points along its length. A well known example of this effect is demonstrated by the tendinous hood structure of the extensor mechanism of the finger (Wilkinson et al., 2003; Valero-Cuevas and Lipson, 2004).

Previous approaches to dynamic simulation, based on either lines-of-force (Delp and Loan, 2000; Garner and Pandy, 2000) or solid mechanics models (Blemker and Delp 2005), are not well-suited for complex structures like the extensor mechanism, where tendons and bones interact in a subtle, but important way. We propose a framework for simulating tendons using a new dynamic modeling primitive, a "strand," which is based on cubic spline curves, with the following desirable attributes: (1) Conceptually simpler routing mechanism, without the need for idealized wrapping surfaces. (2) Full dynamics of muscles and tendons, resulting in a more accurate exchange of forces between tendons and bones. (3) Efficient to simulate.

METHODS

There are three basic building blocks in our framework – rigid bodies for bones, spline-based "strands" for tendons, and virtual sliding points (Lenoir et al. 2004) for constraining strands to slide along arbitrary spline surfaces. The surface constraint works as follows. If a strand is parameterized by s, and the sliding surface is parameterized by (u, v), then the constraint ensures that a fixed point on the strand, $p(s)$, stays on the sliding surface at some location $p_0(u, v)$. The virtual sliding point, (u, v), on the surface is treated as a generalized coordinate of the system, and is included in the system state, along with the configurations of rigid bodies and strands.

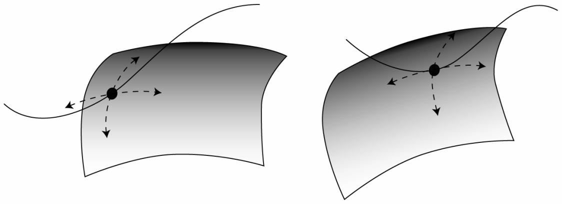

Figure 1: Surface constraint between a strand and an arbitrary rigid surface. The constraint point is fixed to the strand, while it moves freely on the surface.

The final constrained dynamics equation is obtained by discretizing the unconstrained force equations and applying velocity-level constraints (with stabilization) on the generalized coordinates of the system.

$$\begin{pmatrix} M & G^T \\ G & 0 \end{pmatrix} \begin{pmatrix} \Phi^{(k+1)} \\ \lambda \end{pmatrix} = \begin{pmatrix} M\Phi^{(k)} + hf \\ -\mu g \end{pmatrix}.$$

Here, M is the generalized inertia matrix, Φ is the generalized velocity, f is the generalized force, g is the positional constraint, G is the constraint Jacobian, and

λ is the Lagrange multiplier. This sparse linear system is solved at each time step to generate the new generalized velocities, from which we obtain the updated positions of the rigid bodies, strands, and virtual sliding points.

RESULTS AND DISCUSSION

We used a commercial skeleton model (cgCharacter, Adelaide) for the finger bones. The tendon paths were constructed based on standard textbook models in the literature. We then placed the sliding and surface constraints at strategic locations along the tendons so that the penetrations would be minimized across different finger configurations. The PCSA of the tendon was set to 0.123cm^2 and Young's modulus to 421MPa. The input to the model was a set of tensions for the following 5 tendons: extensor digitorum communis, dorsal interosseous, palmar interosseous, flexor digitorum profundus, and flexor digitorum superficialis. Figure 2 shows some of the poses from the dynamic simulation. The extensor tendons slide smoothly on the bone surface, and during certain configurations, they act as flexors by exerting downward forces on the finger.

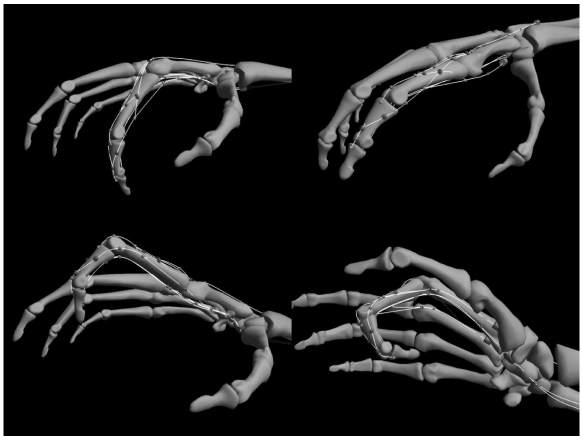

Figure 2: Snapshots from a dynamic simulation of extension/flexion of the index finger.

SUMMARY/CONCLUSIONS

We have developed a new modeling primitive for the simulation of tendinous systems based on the strand model. By using a spline-based approach, our model is able to route tendons efficiently even in complex areas such as the extensor mechanism of the finger. The tendons in our model can, unlike line-based approaches, transmit forces to the bones not only at the origin and insertion, but also at intermediate constraint points on the surface of the bone. We believe that this is important for areas such as the hood of the extensor mechanism and other tendons that span over multiple joints. Our model is computationally much more efficient than solid mechanics models, since it is more suited for the fiber-like structure of tendons.

REFERENCES

Blemker, S. S., Delp, S. L. (2005). Annals of Biomedical Engineering 33 (5), 661–673.

Delp, S. L., Loan, J. P. (2000). Computing in Science & Engineering 2 (5), 46–55.

Garner, B. A., Pandy, M. G. (2000). Computer Methods in Biomechanics and Biomedical Engineering 3, 1–30.

Lenoir, J., Grisoni, L., Meseure, P., Remion, Y., Chaillou, C. (2004). GRAPHITE 2004. ACM Press, New York, NY, USA, 58–64.

Valero-Cuevas, F. J., Lipson, H. (2004). 26th Annual International Conference of the IEEE EMBS. Vol. 2. 4653–4656.

Wilkinson, D. D., Weghe, M. V., Matsuoka, Y. (2003). In: Proceedings of ICRA 2003. Vol 1. 238–243.

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