Biomechanical Analysis of Strabismus – Strengths and Limitations.

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Abstract

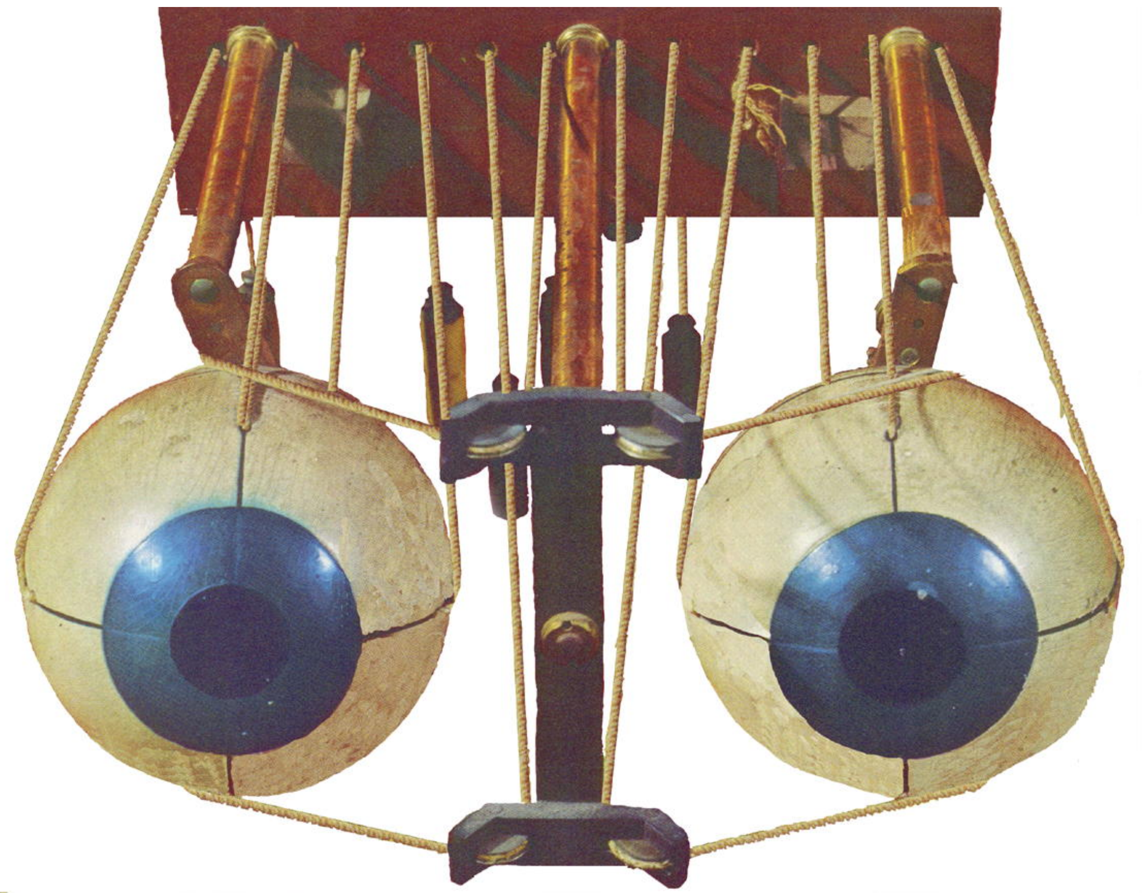
- What is a biomechanical strabismus model?
  - It's structure-based: elements are muscles, bones, forces, innervations, etc, and their geometric and mechanical relationships.
  - It's function oriented: it shows how these elements affect eye alignment and clinical tests.
  - It's a tool, based on first-principles, on physics applied to biological tissues.
- It is not:
  - a lookup table or empirical generalization (useful only in “typical situations”; doesn't clarify mechanisms).
  - a cookbook (it's an aid to understanding, not a replacement).
  - an expert system (not a model of innervations, muscles, etc, themselves, but of the inferences and judgments of human experts.
  - an AI
  - a substitute for clinical judgment
- What is a biomechanical strabismus model useful for?
  - Understanding complex cyclovertical disorders.
  - Improving diagnoses.
  - Developing treatments.
- What biomechanical strabismus models exist?
  - Orbit™1.8
  - SEE++

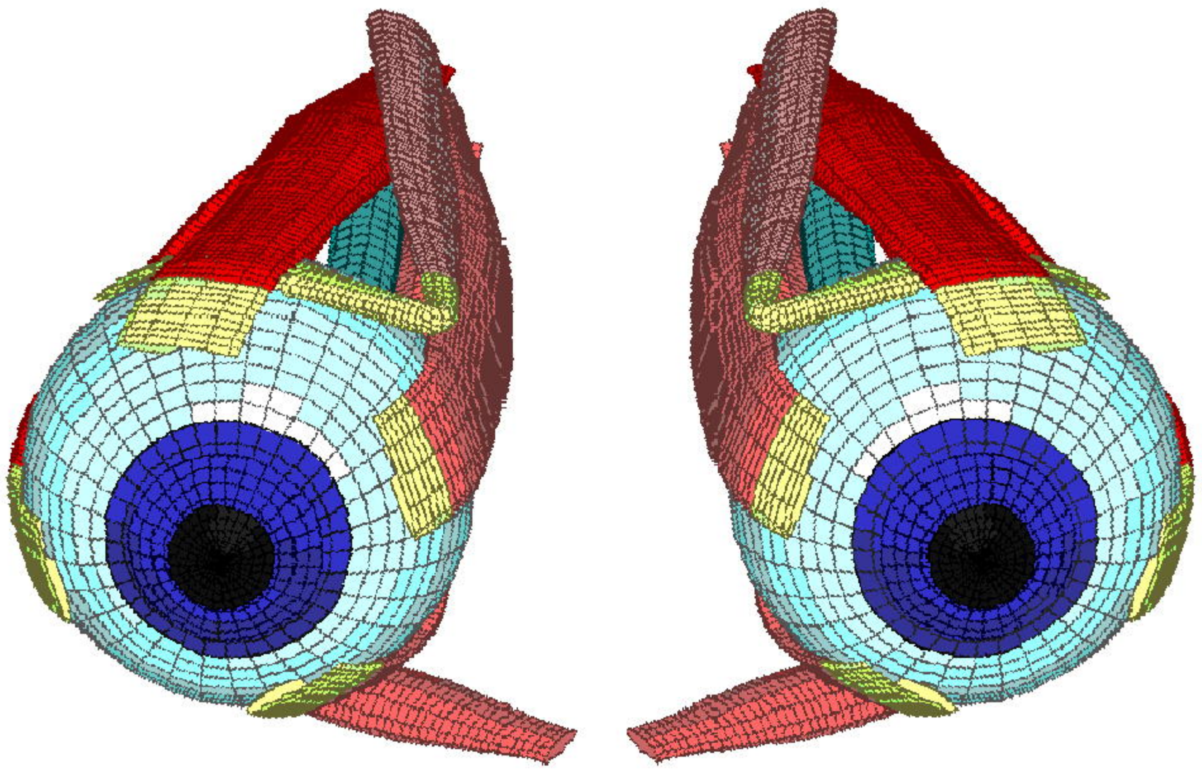
What is Orbit™ 1.8?

- Orbit 1.8 is a tool used to create models of extraocular disorders and treatments, calculate effects on eye alignment, and understand the reasons for those effects in well-defined biomechanical terms.
- It contains a pair of model eyes you can modify to reflect supposed causes of motility disorders and proposed treatments,
- and a simulated eye alignment test, which shows how the modified eyes behave.
- Orbit is used in a trial-and-error mode: Beginning with a pair of simulated normal eyes, you can
  1. alter one or both to reflect your ideas about diagnosis or treatment,
  2. compare Orbit's simulated alignment with clinical alignment measurements or desired treatment outcome,
  3. repeat until you're satisfied with the match. A Parameter Fitter speeds the trial-and error process.

Orbit™ 1.8 is a Computer Ophthalmotrope

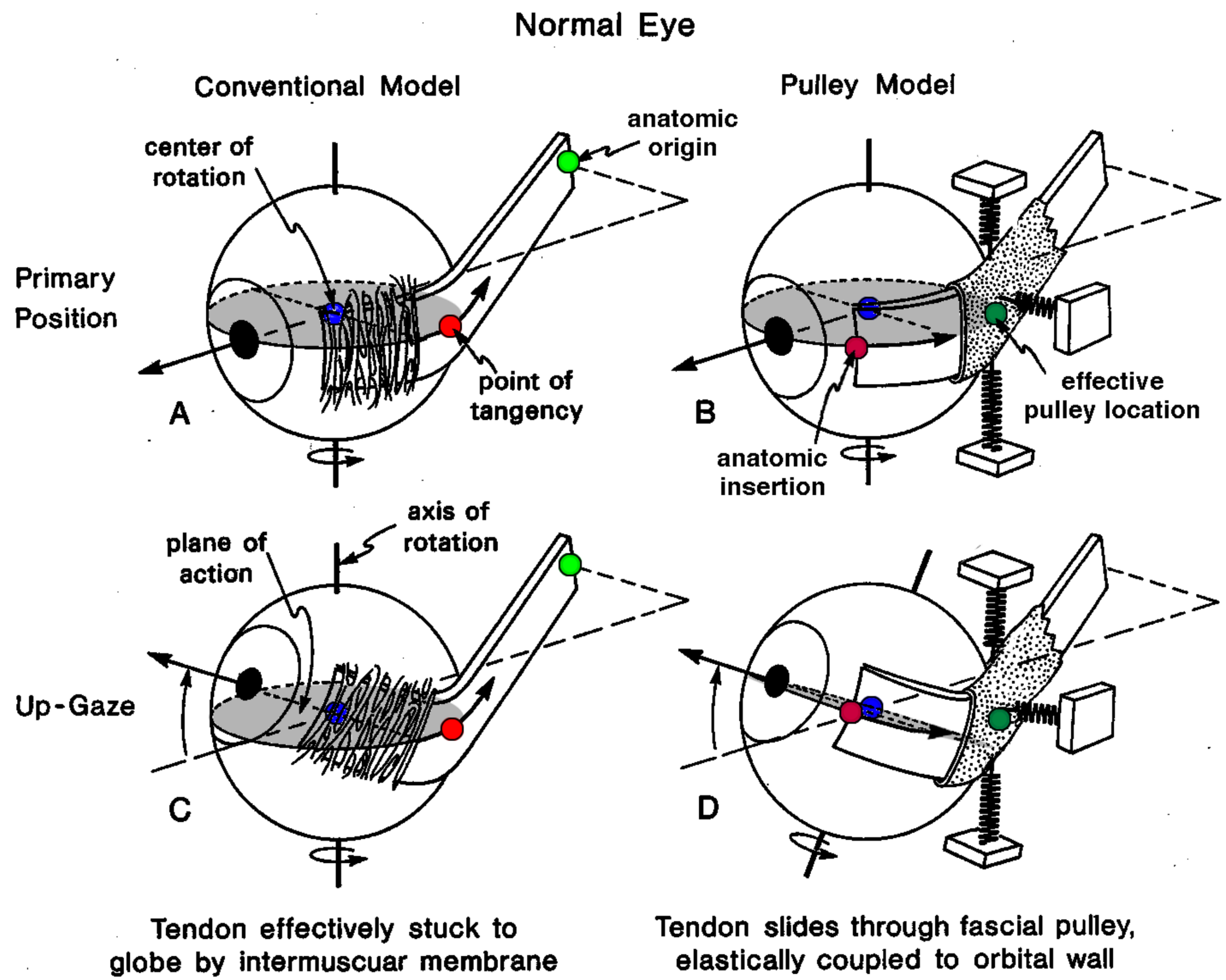
- Thus, Orbit is similar to the ophthalmotropes of Ruete (1845) & Wundt (1862), its main advantage being that its behavior is constrained only by knowledge of orbital mechanics and not by the materials and mechanisms feasible in a physical model.
- For each gaze angle, Orbit pursues iterative solutions involving extraocular connective tissues, and the innervations, paths, and tensions of all muscles in both eyes, according to equations given (in part) by Robinson (1975), Miller and Robinson (1984) and Miller, Pavlovski & Shamaeva (1999).





Orbit 1.0 → Orbit 1.8

- MRI shows that muscle paths are relatively stable in the orbit.
- *Conventional Model* (Robinson's "patch"): connective tissue couples an anterior extent of each muscle to the globe.
- Orbit 1.0 was based on the Conventional Model, causing simulations of muscle transposition surgery to fail because once musculo-global adhesions were cut, EOM bellies could sideslip in the orbit to follow transposed insertions (Miller, 1985).
- Pulley Model: In Orbit 1.8 each muscle passes through connective tissue condensations functioning as pulleys coupled to the orbital wall (Miller, et al, 1984; Miller, et al, 1990; Miller and Demer, 1992).



Orbit 1.8 Solves Three Problems

1. Find Innervation Set:

   What innervations are required to drive a given eye to a given position?

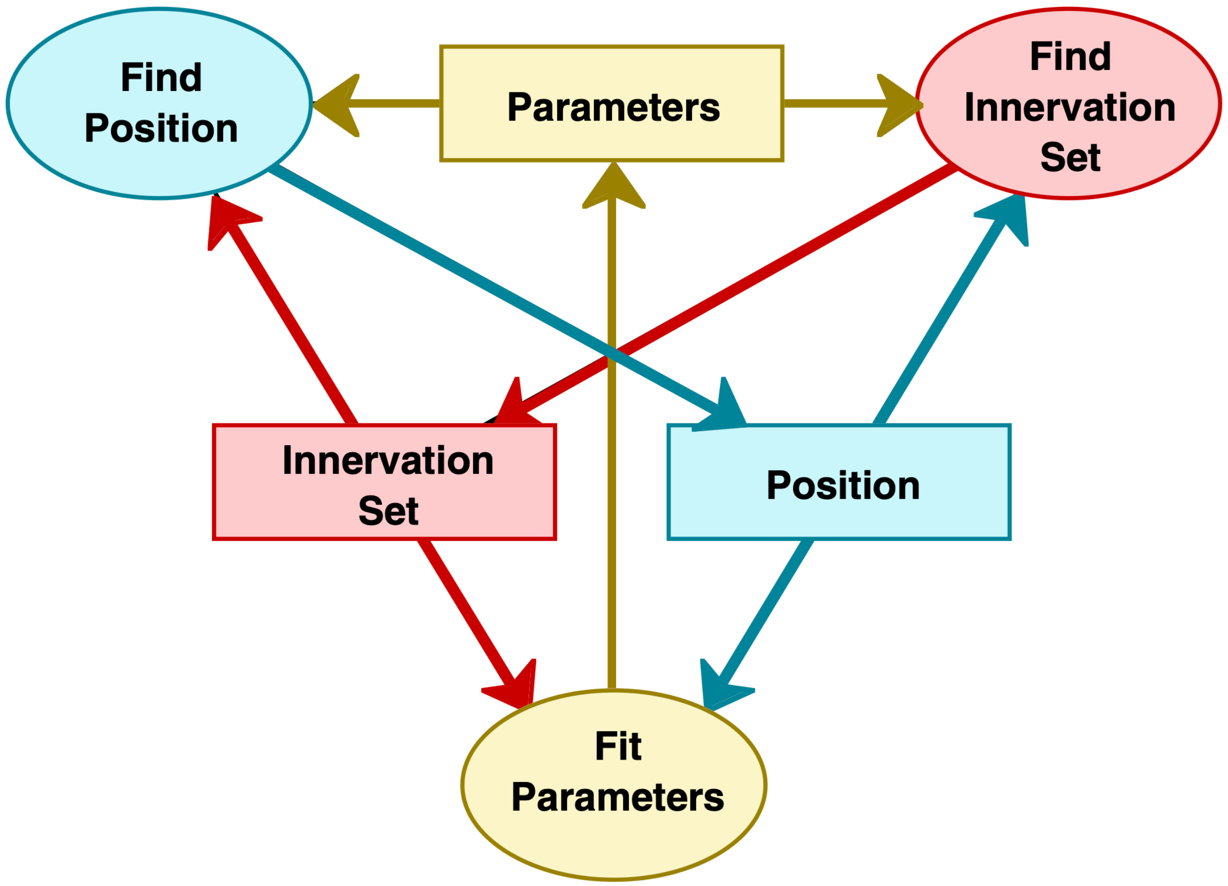
   Given the description of an eye (*parameters*) and the 3 components of an eye *position* (ϑ, φ, ψ), Orbit computes 3 innervations, and then uses Sherrington's Law of Reciprocal Innervation to infer the remaining 3.

2. Find Position:

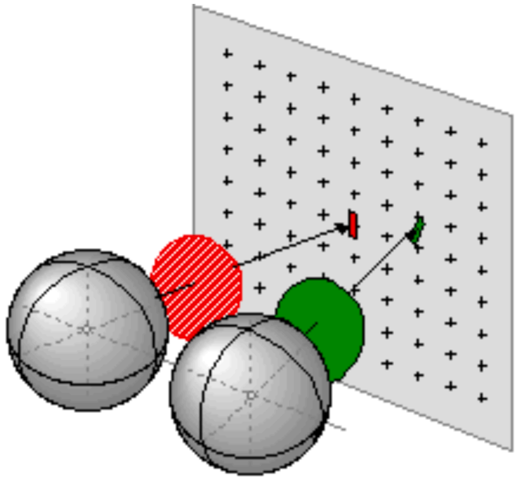
   Where will the eye move if supplied with 6 given innervations?

3. Find Eye Parameters:

   What parameters describe eyes that will move to desired positions under given innervations?



Orbit 1.8 Binocular Model



- Orbit simulates alignment tests in which, eg, the patient's left *fixing eye* foveates the red bar at (0,0) and moves the green bar, seen only by the right, *following eye*, so it appears to lie on top of the red bar.
- Assuming normal retinal correspondence, the relative positions of the 2 bars give the positions of the two eyes. If binocular alignment were normal, the patient would have superimposed the two bars. In the case shown, the right eye is 20° exo-deviated, 5° hyper-deviated, and somewhat excyclo-deviated.

Orbit's simulation follows the clinical test, beginning with the fixing eye.

A. Find the torsion of the (possibly abnormal) fixing eye.

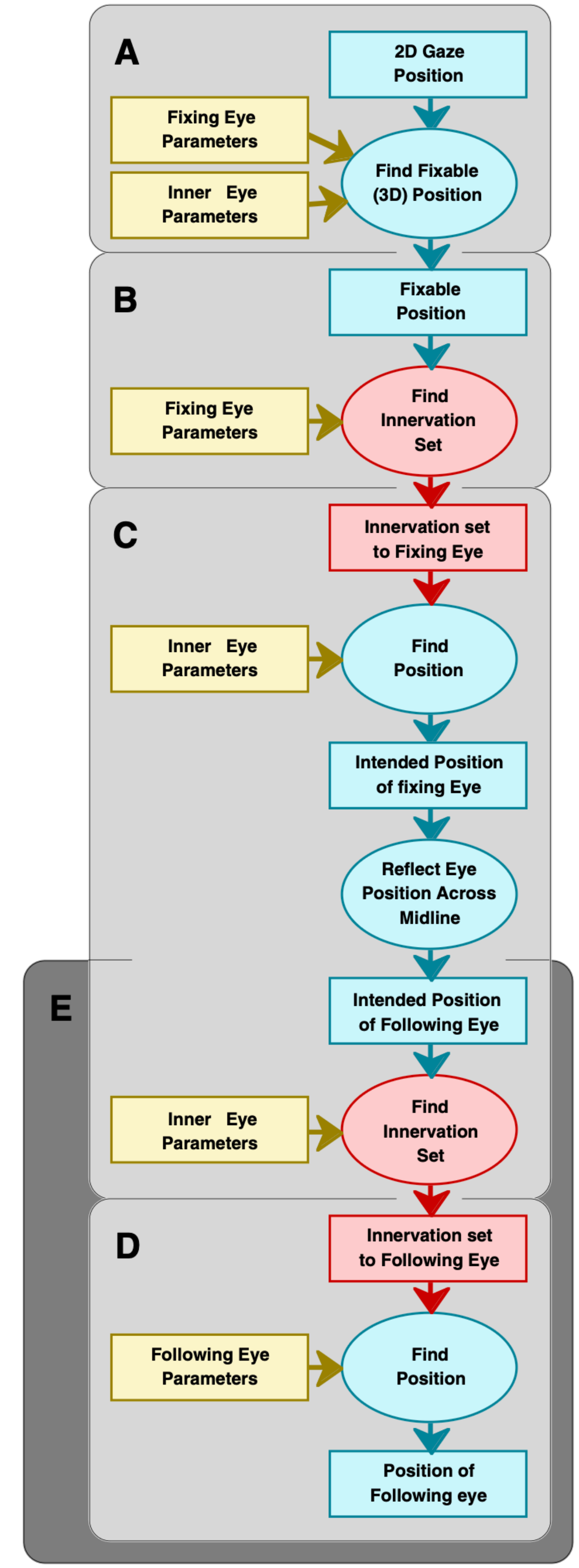
B. Find the innervation set that would drive that eye to the fixation position.

C. Transform those innervations to "position space", reflect them across the midline, and compute the corresponding innervations.

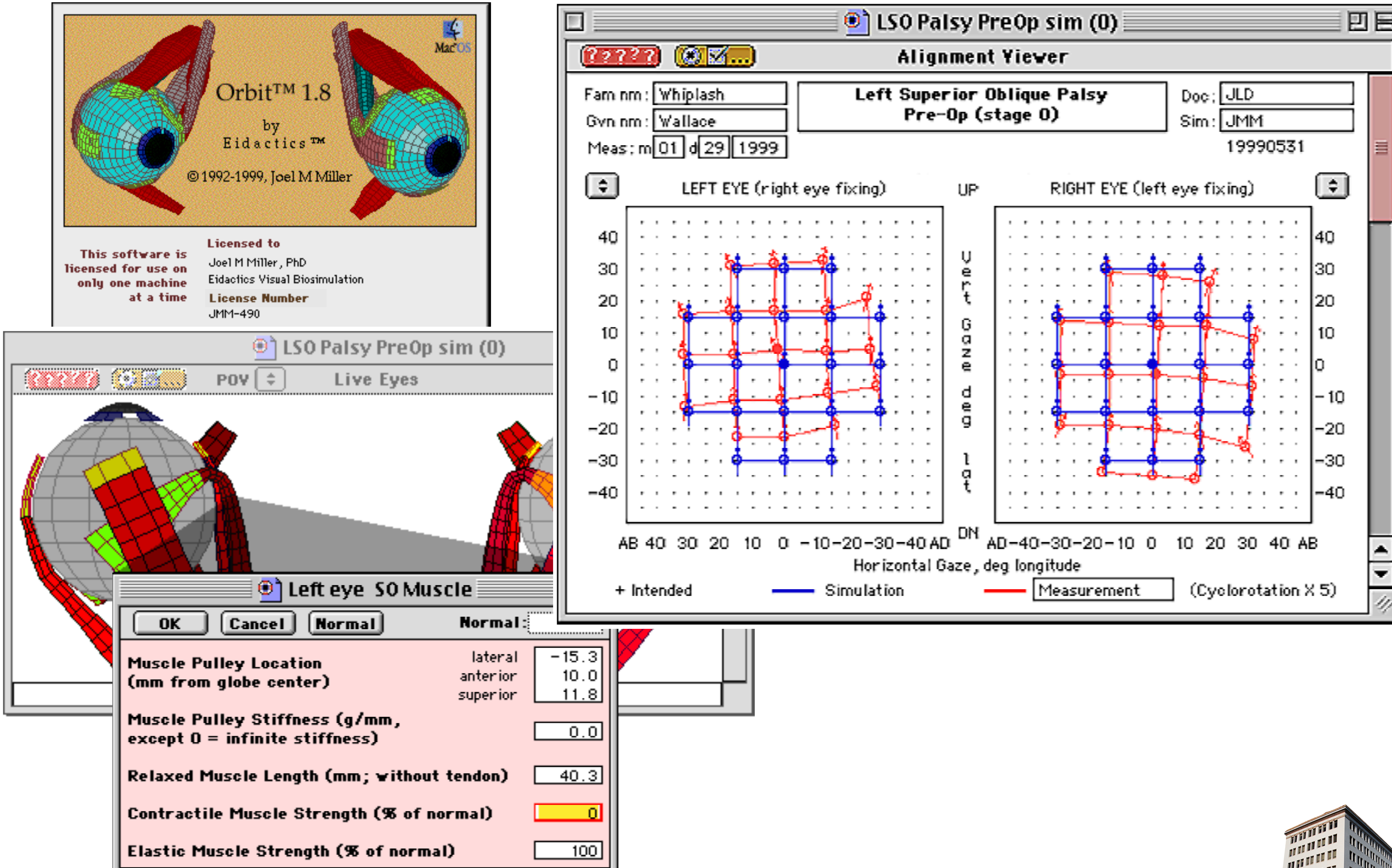
D. Find the positions the (possibly abnormal) following eye would move to under those innervations.

E. If the fixing eye is normal (Orbit 1.0), only these calculations are necessary.

When Following Eye positions match clinical measurements, you've got a *diagnosis* of the patient's disorder in biomechanical terms. Similarly, we can find the muscle manipulations that would cause the model eyes to assume normal, conjugate gaze positions. This would be a *treatment plan*.

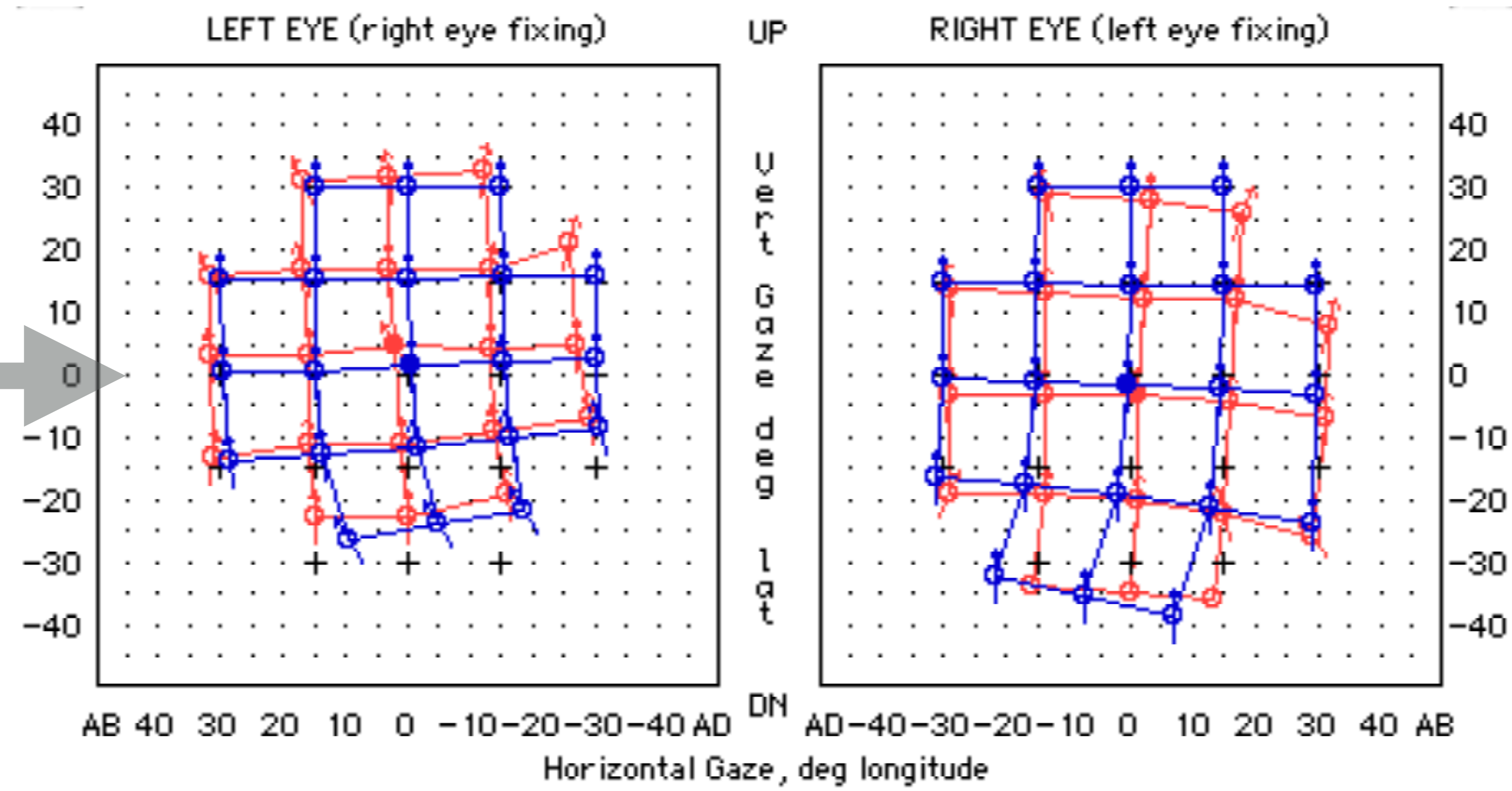


SO Palsy - Pre-Op Simulation (1)

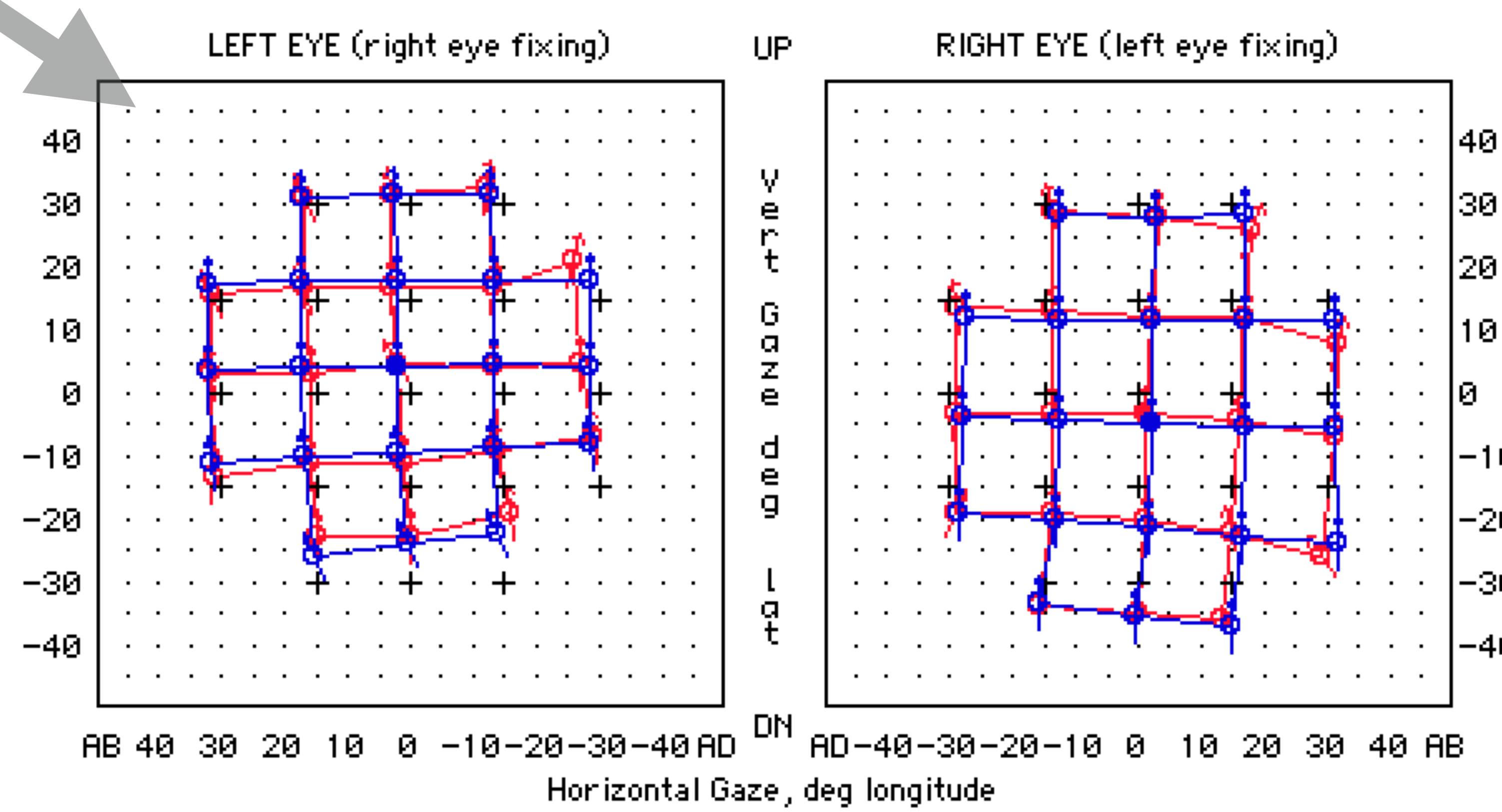


SO Palsy - Pre-Op Simulation (2)

- The simulated left eye matches clinical measurements in showing limited depression in adduction, and a V-pattern, with cyclorotation depending on vertical gaze.
- Thus, SO palsy was a reasonable diagnosis.
- But the simulation shows too much left-hypophoria, suggesting that, as a consequence of the chronically elevated posture of the left eye, the LSR has shortened (2mm).

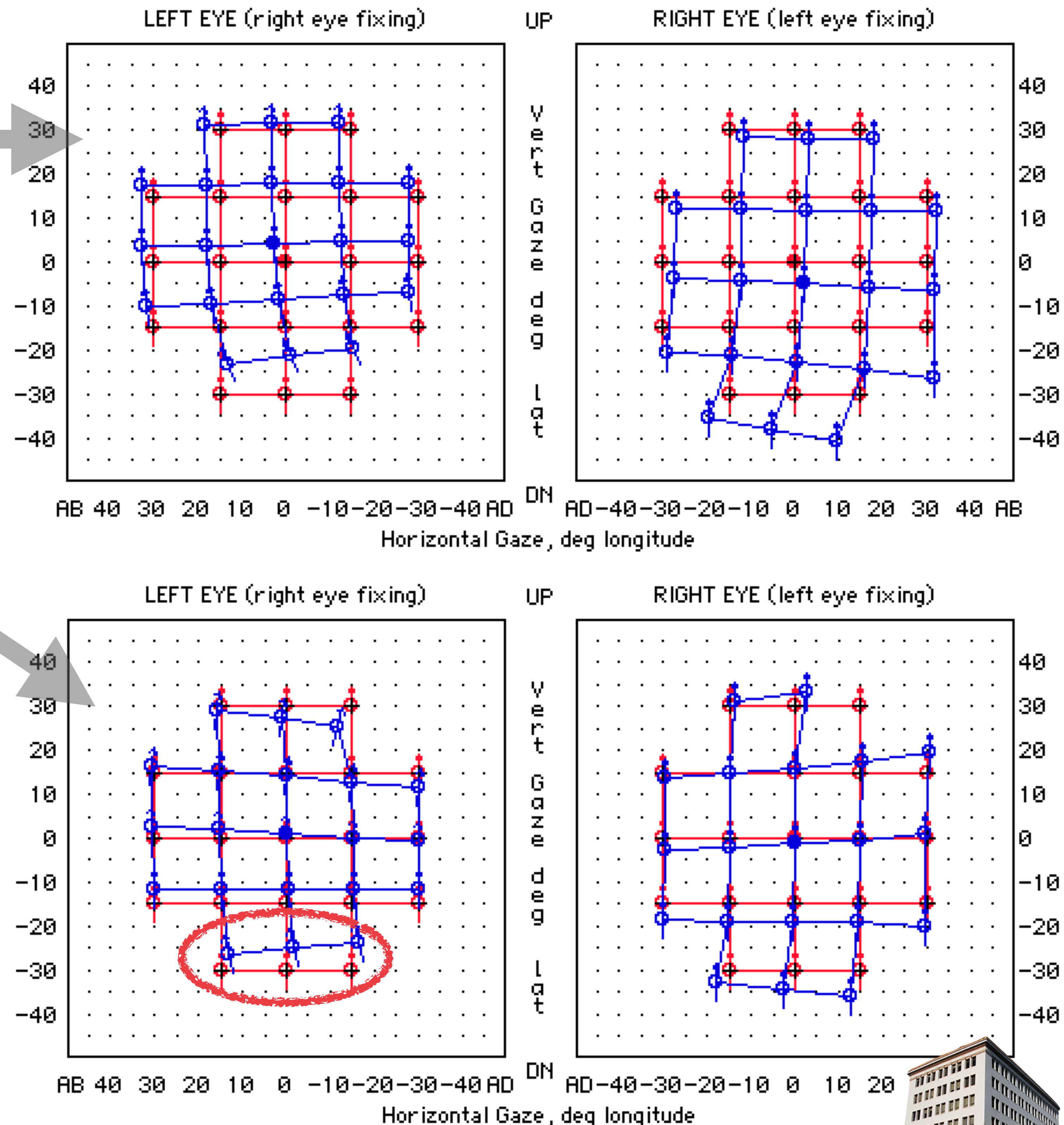


- Other cases might show additional secondary changes, such as: (1) atrophy of the denervated LSO, that is, subnormal elastic force, in addition to its absent contractile force, and (2) adaptation of the cyclovertical muscles which, chronically held at abnormal lengths, have adapted by adding or subtracting serial sarcomeres (Tabary, et al, 1972; Williams & Goldspink, 1973), so that their resting lengths are abnormal.

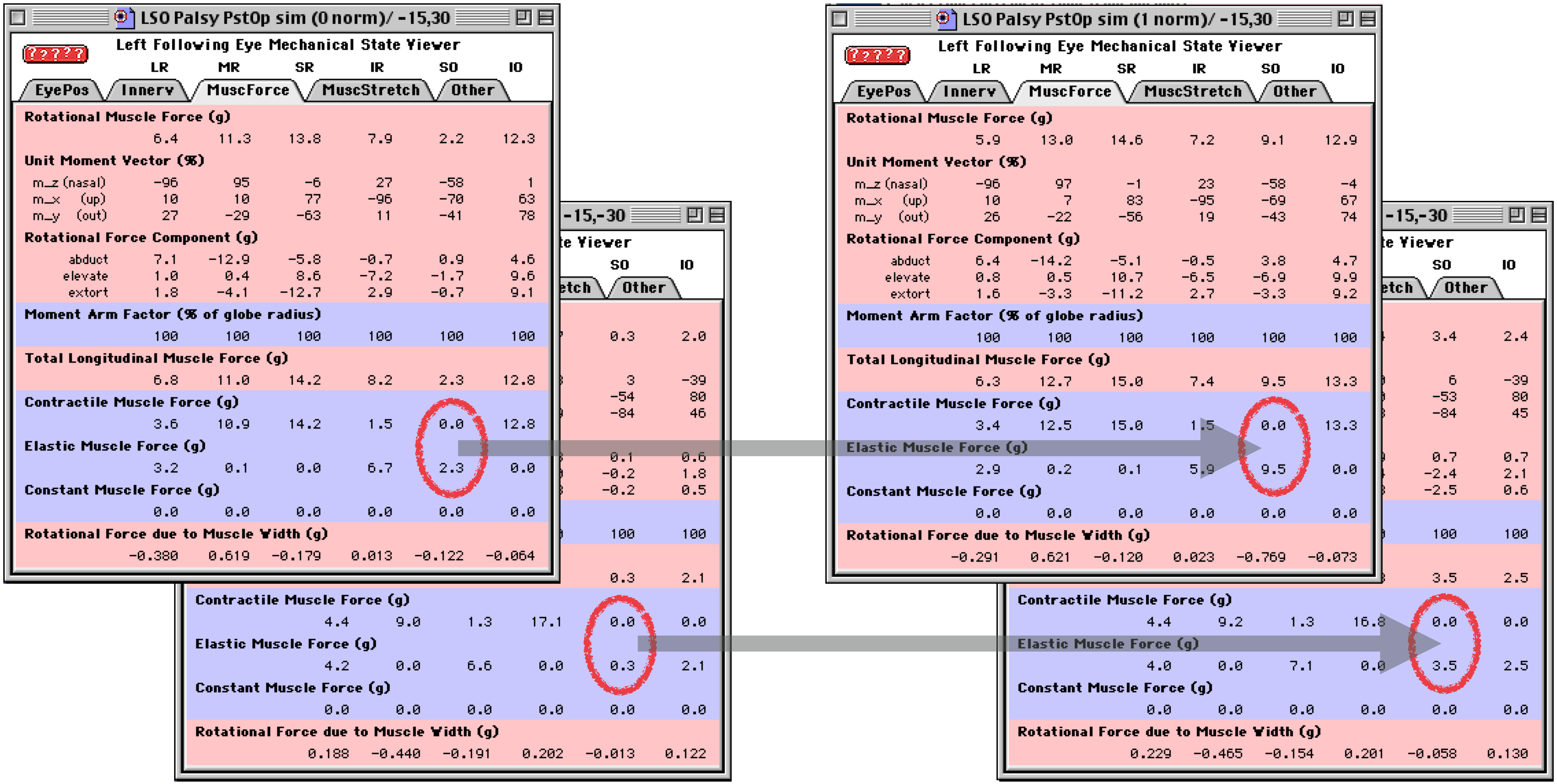


SO Palsy - Post-Op Simulation (1)

- To design a treatment we set the normal measurements we would like the eyes to show.
- An SO tendon tuck of 10mm seems worth a try. But simulation shows that shortening the LSO tendon by 10mm corrects hypertropia in up- and level gaze, but gives little improvement of left eye depression in the important downgaze reading positions.
- Why not?
- Let's look at how did this operation changed forces in upgaze (-15, 30) compared to downsize (-15, -30).



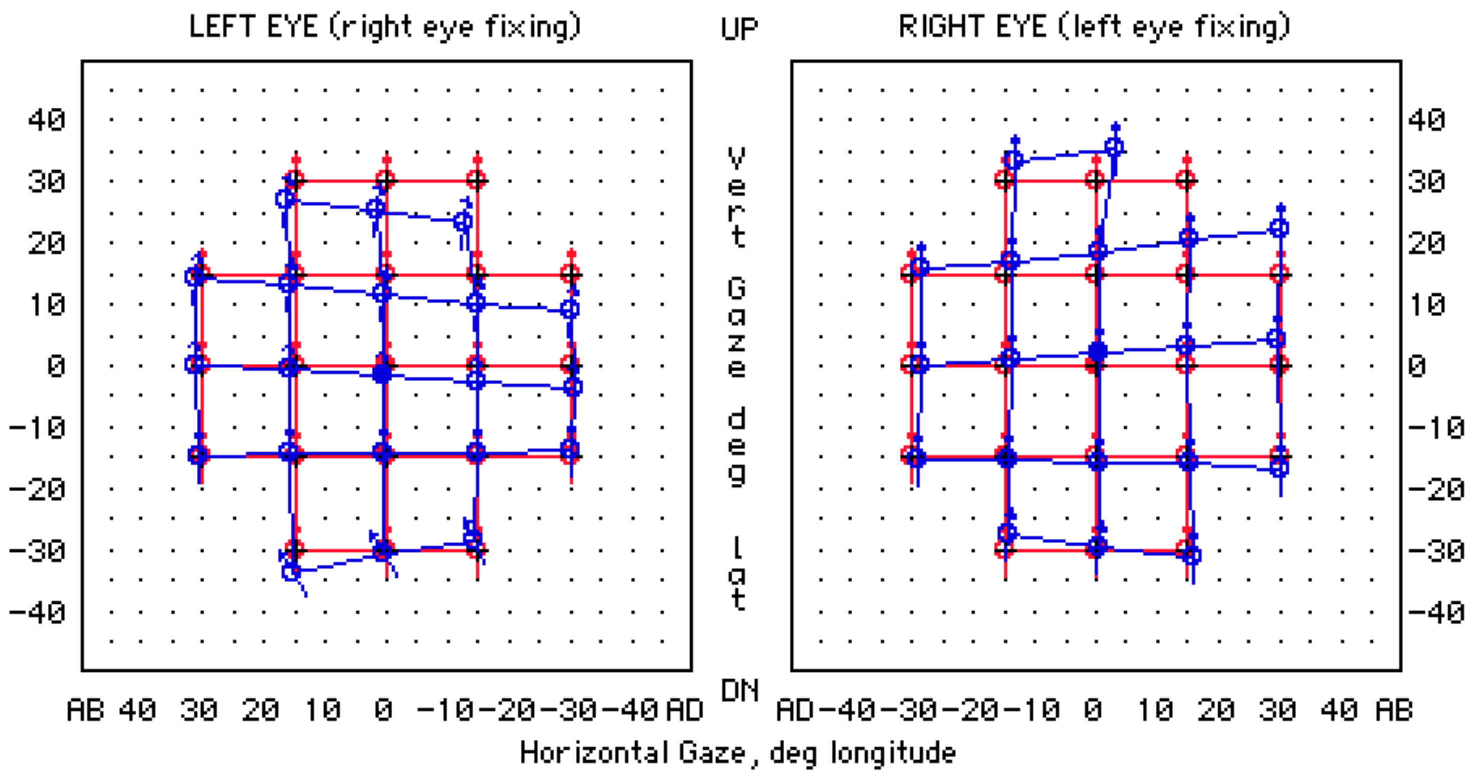
SO Palsy - Post-Op Simulation (2)



- The Mechanical State Viewer shows forces, lengths, etc in each gaze position.
- Whereas LSO elastic force increased substantially from 2.3 to 9.5 g in upgaze,
- there was only a modest increase from 0.3 to 3.5 g in downgaze.
- That’s why the tuck had little effect in downgaze.

SO Palsy - Post-Op Simulation (3)

- RIR recession of ~4 mm gives good alignment in primary position and reading position.
- Apart from recovery of SO contractility, vertical range remains diminished in the SO field of action.



Limitations of Orbit™ 1.8 → Orbit 2.0 (1)

Reciprocal Innervation

Orbit 1.8 solves 3 rotational equilibrium equations to get 3 innervations, and then assumes reciprocal innervation to get the remaining 3. Removing this assumption by also solving 3 translational equations would make Orbit useful for testing the reciprocal innervation relationship and studying its disorders.

Convergence

Gaze in Orbit 1.8 is assumed to be at infinity, rendering comparisons with much clinical data somewhat in error, and making it impossible to simulate differences in binocular alignment when switching between distant and near targets. With a convergence model, it would be straightforward to specify AC/A ratio, broadening the ability to simulate clinical alignment tests at varying distances.

Limitations of Orbit™ 1.8 → Orbit™ 2.0 (2)

Simulate clinical "tilt" tests:

Commonly used to diagnose oblique muscle dysfunctions, there is good population data on the magnitude of ocular torsion in response to tilt under various situations (Miller, 1962; Merker and Held, 1981; Robinson, 1985; Ott, 1992), which could be used to model the dependence of binocular innervations on otolith and neck afferent inputs. Treating these inputs separately would make the model useful with vestibular patients.

Properly model the inferior oblique muscle:

Implement Lockwood's Ligament and the neurofibrovascular bundle (Stager, 1996). These modifications require implementing muscle-to-muscle coupling, and a mid-muscular leash. Without these improvements, IO surgery cannot be reliably simulated.

Make muscle surfaces part of the biomechanical model

Surfaces are currently only in the graphical visualization. This would make it possible to model mechanical effects of muscle intersection, which may be important in normal as well as abnormal eyes.

Orbit 2.0

- Orbit 1.8 is 25 years old.
- It runs under MacOS in an emulation environment created by Dr Steven Archer.
- Rewriting it would be an excellent project, but one that should not be underestimated.
- I'm happy to provide the Orbit 1.8 source code to anyone interested in undertaking this project.