An Open-Source OpenSim Oculomotor Model for Kinematic and Dynamic Simulation

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Abstract

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Introduction

Methods

Eye Globe

he orbital plant consists of the globe (eyeball), three pairs of extraocular muscles, and connective tissues. The size of an emmetropic human adult eye is approximately 24.2 mm (transverse, horizontal) x 23.7 mm (sagittal, vertical) x 22.0–24.8 mm (axial, anteroposterior) with no significant difference between sexes and age groups. In the transverse diameter, the eyeball size may vary from 21 mm to 27 mm. Thus, it can be approximated by a solid sphere with 12mm radius. The eyeball was constructed in Blender, an open-source software 3D creation Software. We used a spherical mesh with 32 segments and 12 rings, to construct the vitreous humor (body) as solid sphere and a conical plate to construct the cornea. The weight of an average human eye is 7.5grams and the moment of inertia can be calculated similarly as in the case of a spherical homogenous and isotropic object with radius 12mm ($\boldsymbol{I} = 2/5mr^2$ at the center of mass).

Muscle Paths and Pulleys

Table 1: Muscle parameters: muscle origin, insertion and maximum force.

Muscle	**Origin**			**Pulley**			**Insertion**		
	Ox	***Oy***	***Oz***	***Px***	***Py***	***Pz***	***Ix***	***Iy***	***Iz***
LR	-0.034	0.0006	-0.013	-0.0102	0.0003	0.012	0.0065	0	0.0101
MR	-0.030	0.0006	-0.017	-0.0053	0.00014	-0.0146	0.0088	0	-0.0096
SR	-0.0317	0.0036	-0.016	-0.0092	0.012	-0.002	0.0076	0.0104	0
IR	-0.0317	-0.0024	-0.016	-0.0042	-0.0128	-0.0042	0.00805	-0.0102	0
SO	0.0082	0.0122	-0.0152	-0.030834	0.001145	-0.01644	0.0044	0.011	0.0029
IS	0.0113	-0.0154	-0.0111	-0.00718	-0.0135	0	-0.008	0	0.009

Passive Connective Tissues

The passive connective tissues of the eyeball apply a restoring force, which brings the globe back to the central position when the net force from the Extraocular Muscles (EOMs) is zero. These tissues include all non-muscular suspensory tissues, such as Tenon's capsule, the optic nerve, the fat pad and the conjunctiva. The force-displacement curve of the net elasticity can be represented as

$$\boldsymbol{f}_t = -k_p\boldsymbol{q} - k_c 10^{-3}\boldsymbol{q}^3 - k_d * \dot{\boldsymbol{q}} \tag{1}$$

where, $\boldsymbol{f}_t$ represents the passive tissue forces, $k_p = 0.33\text{g / deg}$, $k_p = 1.56\text{g / (deg^3)}$ (TODO: convert to Nm / rad) and $k_v = 10^{-4}\text{Nm s / rad}$ the constants and $\dot{\boldsymbol{q}} \in \Re^3$ the rotational coordinates of the model. These forces serve the eye's stabilization, and are modeled using `OpenSim`'s expression based coordinate force.

Model Validation

To meet good fidelity criteria, a model requires to be verified and validated. In our study, verification in oculomotor models was performed by comparing the force-length characteristic curves of the modeled

EOMs to published data. These data include only the lateral rectus characteristic curves. However, we can make a safe assumption that the other muscles have similar properties. More characteristic curves showing the force-length relationship of the other EOMs, as well as the changes in muscle length with rotation in all directions, are presented in the end of this report. Further verification can be done by comparing the model's joint forces produced during horizontal movement with clinically collected data, but these data are not available. Validation was performed by simulating and analyzing synthesized eye movements while ensuring that Listing Law was obeyed by maintaining zero torsion in secondary gaze positions, and by testing if the assessed innervations are sufficient in fixating the eye at a desired position.

Results

Conclusion

We manage to construct a complete ocular model that represents the ocular motility of a normal human eye. The model can be used to drive simulations of different eye movement systems and be derive some inference about the excitation and activation patterns. The verification and validation of the model showed that it matches the data found in literature and it is able to produce synthetized movements. We even showed that the simulation results produced by static optimization and forward dynamics in OpenSim are less satisfactory than the proposed solution where we used a PD controller to minimize the tracking error between the desired and estimated trajectory of saccadic movements. The desired kinematics were tracked within a maximum Root Mean Square Error (RMSE) of and in horizontal and vertical saccades respectively. With the application of the controller, a very rapid instantaneous acceleration and a constant velocity to sustain clear vision is attained. The produced activation levels were in accordance with the descriptions found in the bibliography and the highest activation levels were shown only during the time intervals when the main agonist muscle was activated.