Biomechanical costs and grip planning: a model

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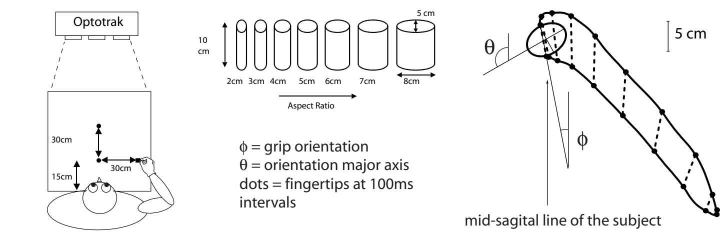
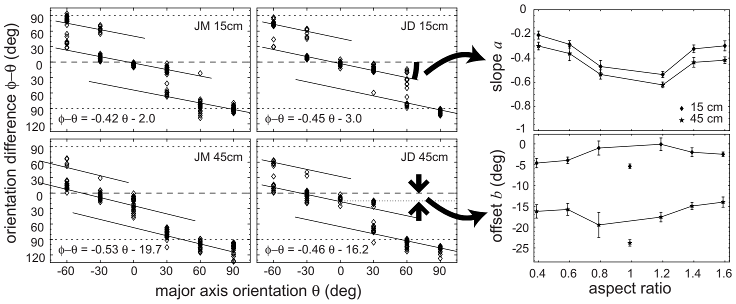
Introduction

Cylinders with an elliptical circumference can best be grasped along one of their principal axes. Cuijpers, Brenner and Smeets (2004) found that such cylinders are indeed grasped near their principal axes, but with systematic 'errors'. Here we investigate whether these errors are just a trade-off between an optimal and a comfortable grip or whether perceptual errors are involved.

Experimental findings





- The grip orientation switches between three different modes
- Each mode depends linearly on the cylinder orientation:

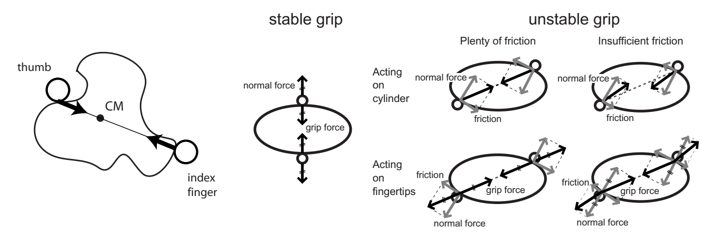
$$\phi_k = (1+a)\,\theta_k + b, \quad \text{where } \theta_k = \theta_{major} + k\,90$$

- Slopes and offsets depend on the cylinder's aspect ratio

Physical constraints

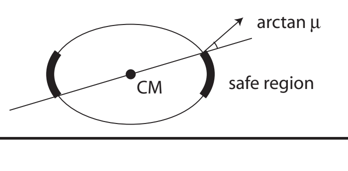
Sufficient friction:

$$\left\{\begin{array}{l}\sum \text{forces} = 0\\ \sum \text{torques} = 0\end{array}\right. \Leftrightarrow \left\{\begin{array}{l}\textit{grip locations} \text{ on line through CM}\\ \textit{grip forces} \text{ equal and opposite}\\ \text{sum of } \textit{lift forces} \text{ equals gravity}\\ \text{horizontal torque is zero}\end{array}\right.$$



Insufficient friction:
- grip force not fully compensated → fingers will slip
- net force and net torque no longer zero → object moves

Elliptical cylinders:
- optimal grip orientations are along the major and minor axes
- angle between surface normal and grip axis < arctan μ , (where friction < μ * normal grip force)



Model assumption

The grip orientation is a weighted average of the optimal grip orientation θ_k and the comfortable grip orientation ϕ_c:

$$\phi_k = w\,\theta_k + (1-w)\,\phi_c$$

Biomechanical cost/gain function

Gain due to optimal grip orientation: $G_{optimal}(\phi) = -\,w\,(\phi - \hat{\theta}_k)^2$

Gain due to comfortable orientation: $G_{comfort}(\phi) = -\,(1-w)\,(\phi - \hat{\phi}_c)^2$

Variability in movement execution: $p(\phi|\phi_{planned}) = norm(\phi_{planned}, \sigma_\phi^2)$

Variability in perceived orientation: $p(\hat{\theta}_k|\theta_k) = norm(\theta_k, \sigma_\theta^2)$

Uncertainty in comfortable orientation: $p(\hat{\phi}_c|\phi_c) = norm(\phi_c, \sigma_{\phi_c}^2)$

Biomechanical gain function: $G(\phi) = G_{optimal}(\phi) + G_{comfort}(\phi)$

Then the expected gain is: $EG(\phi_{planned}) = \int G(\phi)\, p(\phi|\phi_{planned})\, d\phi$

We have derived that the expected gain is maximal when:

$$\phi_{planned} = w\,\hat{\theta}_k + (1-w)\,\hat{\phi}_c$$

with maximum: $MEG_k = -\,\sigma_\phi^2 - w(1-w)(\hat{\theta}_k - \hat{\phi}_c)^2$

Results

- The gain function leads to the desired linear relation with $w = 1+a$.

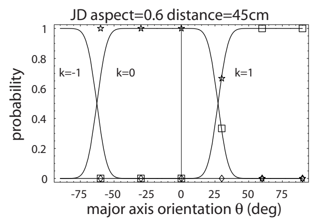
  It also specifies the variability:

$$E\phi = (1+a)\,\theta_k - a\,\phi_c$$

$$\text{var}\,\phi = \sigma_\phi^2 + (1+a)^2\,\sigma_\theta^2 + a^2\,\sigma_{\phi_c}^2$$

- For the circular cylinder $a = -1$ → $\phi_c = E\phi_{circ}$ and $\sigma_\phi^2 + \sigma_{\phi_c}^2 = \text{var}\,\phi_{circ}$
- The switching between grip orientations follows automatically from choosing k_{max} so that $MEG_{k_{max}}$ is maximal: choose the mode closest to the comfortable grip orientation

Observed and predicted switching between major and minor axes using data from circular cylinder



Data from circular cylinder

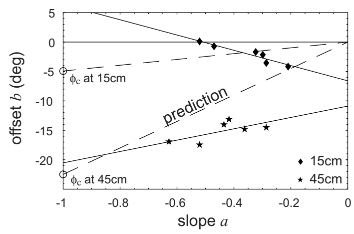
$\phi_c = E\phi_{circ} = -17.8°$

$\sigma_{\phi_c} \sim \text{var}\,\phi_{circ} = 5.9°$

- The offsets in grip orientation are related to the slopes by:

$$b = -a\,\phi_c$$

However:



Conclusions

- We modeled the linear relation between grip and cylinder orientation and the switching between grip axes, but ...
- The predicted relation between offsets and slopes is not observed
- The mismatch depends on the cylinder's shape, suggesting a perceptual origin: the perceived cylinder orientation is biased

Cuijpers RH, Smeets JBJ and Brenner E. On the relation between object shape and grasping kinematics. J Neurophysiol 91:2598-2606, 2004.