1 Estimation of m_0

The equivalence between the human arm mechanism and the model was established by relating the mass m_0 of the cart to the inertia of the arm segments. It was assumed that the hand moves horizontally. The human arm was modeled as the slider crank mechanism shown in Figure 1. The parameters of the mechanism were set according to the average human arm segment (Deleva, 1996) (see figure legend for values and definitions).

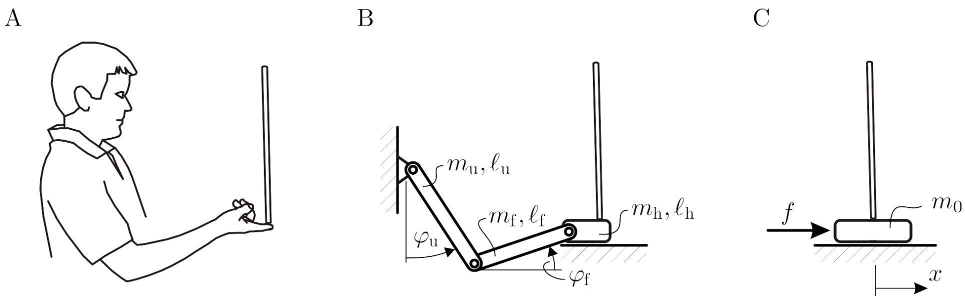

Figure 1: A, Subject balancing stick on fingertip. B, Slider crank model of the arm used to estimate the equivalent mass of the cart for the pendulum-cart model. The mass and length of the upper arm, forearm and hand are, respectively, $m_{\mathrm{u}} = 1.775$kg, $\ell_{\mathrm{u}} = 0.2874$m, $m_{\mathrm{f}} = 1.015$kg, $\ell_{\mathrm{f}} = 0.2666$m, $m_{\mathrm{h}} = 1.015$kg and $\ell_{\mathrm{h}} = 0.0821$m. C, Pendulum-cart model for stick balancing with equivalent mass.

The equivalence of the models is based on the equivalence of their kinetic energy. The kinetic energy of the arm mechanism can be given as

$$E_{\mathrm{kin,arm}} = \frac{1}{2}m_{\mathrm{u}}v_{\mathrm{u}}^2 + \frac{1}{2}J_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}^2 + \frac{1}{2}m_{\mathrm{f}}v_{\mathrm{f}}^2 + \frac{1}{2}J_{\mathrm{f}}\dot{\varphi}_{\mathrm{f}}^2 + \frac{1}{2}m_{\mathrm{h}}v_{\mathrm{h}}^2, \tag{1}$$

where v_{u}, v_{f} and v_{h} are the velocities of the center of gravity of the upper arm, forearm and hand, respectively, and J_{u} and J_{f} are the moment of inertia with respect to the normal line via the center of gravity of the upper arm and the forearm. Assuming a homogeneous cylindrical arm segment, we have $J_{\mathrm{u}} = \frac{1}{12}m_{\mathrm{u}}\ell_{\mathrm{u}}^2$ and $J_{\mathrm{f}} = \frac{1}{12}m_{\mathrm{f}}\ell_{\mathrm{f}}^2$. The velocity vectors of the center of gravity of the upper arm, forearm and hand can respectively be given as

$$\mathbf{v}_{\mathrm{u}} = \begin{pmatrix} \frac{1}{2}\ell_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}\cos\varphi_{\mathrm{u}} \\ \frac{1}{2}\ell_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}\sin\varphi_{\mathrm{u}} \\ 0 \end{pmatrix} = \begin{pmatrix} v_{\mathrm{u}x} \\ v_{\mathrm{u}y} \\ 0 \end{pmatrix}, \tag{2}$$

$$\mathbf{v}_{\mathrm{f}} = \begin{pmatrix} \ell_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}\cos\varphi_{\mathrm{u}} - \frac{1}{2}\ell_{\mathrm{f}}\dot{\varphi}_{\mathrm{f}}\sin\varphi_{\mathrm{f}} \\ \ell_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}\sin\varphi_{\mathrm{u}} + \frac{1}{2}\ell_{\mathrm{f}}\dot{\varphi}_{\mathrm{f}}\cos\varphi_{\mathrm{f}} \\ 0 \end{pmatrix} = \begin{pmatrix} v_{\mathrm{f}x} \\ v_{\mathrm{f}y} \\ 0 \end{pmatrix}, \tag{3}$$

$$\mathbf{v}_{\mathrm{h}} = \begin{pmatrix} \ell_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}\cos\varphi_{\mathrm{u}} - \ell_{\mathrm{f}}\dot{\varphi}_{\mathrm{f}}\sin\varphi_{\mathrm{f}} \\ \ell_{\mathrm{u}}\dot{\varphi}_{\mathrm{u}}\sin\varphi_{\mathrm{u}} + \ell_{\mathrm{f}}\dot{\varphi}_{\mathrm{f}}\cos\varphi_{\mathrm{f}} \\ 0 \end{pmatrix} = \begin{pmatrix} v_{\mathrm{h}} \\ 0 \\ 0 \end{pmatrix}. \tag{4}$$

Note that the motion of the hand is assumed to be horizontal. Since the mass of the stick ($m \in [0.006\text{kg}, 0.02\text{kg}]$) is negligible compared to the mass of the arm-hand mechanism (cart), the kinetic energy of the pendulum cart model is

$$E_{\mathrm{kin,cart}} = \frac{1}{2} m_0 \dot{x}^2. \tag{5}$$

Angular velocities $\dot{\varphi}_{\mathrm{u}}$ and $\dot{\varphi}_{\mathrm{f}}$ can be given as function of v_{h} using (4) as

$$\dot{\varphi}_{\mathrm{u}} = \frac{v_{\mathrm{h}}\cos\varphi_{\mathrm{f}}}{\ell_{\mathrm{u}}\cos(\varphi_{\mathrm{u}} - \varphi_{\mathrm{f}})} \tag{6}$$

$$\dot{\varphi}_{\mathrm{f}} = \frac{v_{\mathrm{h}}\sin\varphi_{\mathrm{u}}}{\ell_{\mathrm{f}}\cos(\varphi_{\mathrm{u}} - \varphi_{\mathrm{f}})} \tag{7}$$

Using the equivalences $E_{\mathrm{kin,arm}} = E_{\mathrm{kin,cart}}$ and $v_{\mathrm{h}} = \dot{x}$ and substituting $v_{\mathrm{u}}^2 = v_{\mathrm{u}x}^2 + v_{\mathrm{u}y}^2$ and $v_{\mathrm{f}}^2 = v_{\mathrm{f}x}^2 + v_{\mathrm{f}y}^2$ according to (2) and (3) and $\dot{\varphi}_{\mathrm{u}}$ and $\dot{\varphi}_{\mathrm{f}}$ according to (6) and (7), one can calculate the equivalent mass m_0 of the cart. Assuming φ_{u} and φ_{f} for the arm segment vary about their mean values, $\varphi_{\mathrm{u}} \approx 20^o$ and $\varphi_{\mathrm{f}} \approx 10^o$, the mass of the cart is obtained to be $m_0 = 1.2$kg.

2 Eensemble Average for determination of time delay

During the blank out the subject was instructed to "keep balancing". This is what the subject woiuld normally due when there is an eye blink (typical duration < 300 ms). However, the movements of the stick and fingertip which are uncorrelated with the end of the blank out make it difficult to determine with precision the oinset of the correctuve movements and hence the time delay, τ. This is true whether we determine τ from the changes in the vertival displacement angle (Figure 2a), θ, where

$$\theta = \frac{\sqrt{(AP_{\mathrm{t}} - AP_{\mathrm{b}})^2 + (ML_{\mathrm{t}} - ML_{\mathrm{b}})^2}}{\ell_{\mathrm{m}}},$$

or the velocity of the movements of the fingertip, $\dot{x}$ (Figure 2b). To circumvent this problem we computed the ensemble average by adding up all of the trials and dividing by the number of trials. With this procedure changes in θ and $\dot{x}$ which are uncorrelated with the end of the blank out average to zero. As can be seen it is much easier to determine τ using the ensemble average. This type of averaging procedure is similar to that used to determine the latencies of evoked potentials (see, for example, D. Regan (1975). Color coding of pattern responses in man investigated by evoked potential feedback and direct plot techniques. *Vision Res.* 15: 175-183).

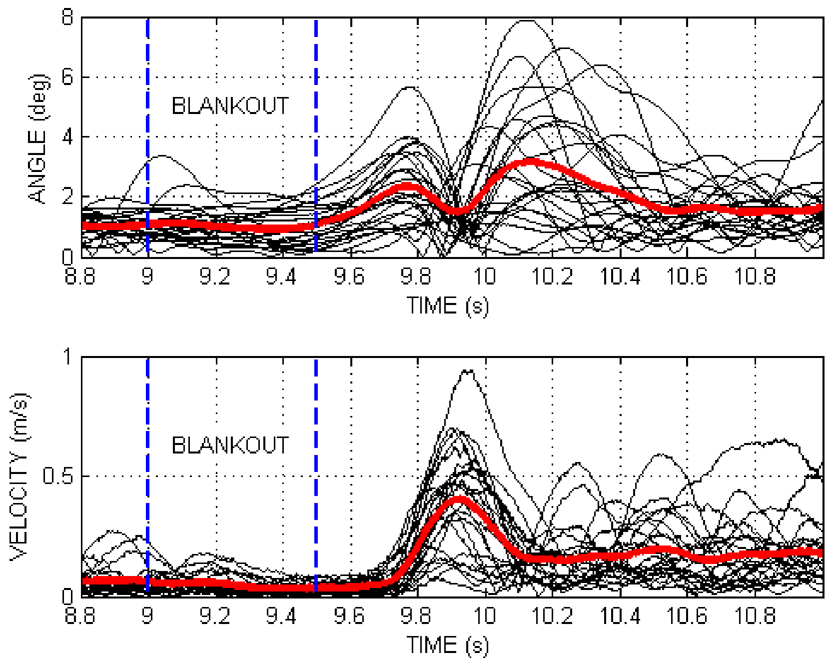

Figure 2: a) Changes in the vertical displacement angle, θ, and b) fingertip velocity, $\dot{x}$, for a 0.5s blank out for Subject E1 balancing a 0.91m stick on the surface of a table tennis racket. Twenty-five (25) consecutive trials are shown. In both case the ensemble average is shown by the red line.