Expert stick balancing: Lévy distributions and the edge of stability

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Summary. An important step towards preventing falls in the elderly is the identification of variables to assess the risk of falling. Stick balancing on the fingertip is a paradigm of time-delayed balance control in which the interplay between skill acquisition and task difficulty can be readily investigated. Here we show that the probability distribution of the changes in speed of the fingertip during stick balancing becomes "long-tailed" in situations in which the risk of stick falling is highest. Thus large deviations in the magnitude of corrective movements for maintaining balance are also the harbingers for fall occurrence.

Introduction

Falls in the elderly are a major source of morbidity and mortality. Video capture of falls in elders show that the falls are often not related to "slips and trips", but commonly arise because the nervous system fails to properly integrate information provided by sensory feedback with cortical internal models developed previously over decades of balancing experiences [1]. Thus suitable paradigms for falling are not simply those related to the stabilization of an inverted pendulum, but are more related to the development of expertise of stick balancing at the fingertip [2, 3]. Subjects who are expert in stick balancing can maintain a 0.3m stick balanced on their fingertip for 240s [2]. This achievment is quite remarkable since the time delay is quite long (≈ 0.23s) and there is a 0.8° dead zone for the estimation of the vertical displacement angle of the stick in the saggital plane. Recently we proposed a switching-type, pendulum cart model for expert stick balancing that uses an internal model to compensate for the time delay by predicting the sensory consequences of the stick's movements [2]. This model predicts that feedback gains are tuned close to the edge of stability as suggested previously [4, 5]. This strategy optimizes balance control with a combination of quick maneuverability and minimum energy expenditure. At the edge of stability it is expected that control gains can be stochastically forced back and forth across the stability boundary leading to the appearance of "long-tailed", or Lévy-type distributions in the changes in speed, ΔV, of the movements of the fingertip [6, 7]. Here we show that a Lévy distribution in ΔV arises in two situations in which the risk of stick falling is the highest: novices learning to stick balance and experts when the balance task is made difficult by shortening the stick length. The observation that large deviations in ΔV arise as the balance task becomes more difficult supports the possibility of developing statistical tests to detect an increased risk for falling before the falls occur.

Methods

Human subjects

This study was approved by the institutional review board at Claremont McKenna College in accordance with the currently applicable U. S. Public Health Service guidelines. All participants provided informed consent for all research testing. The stick balancing time on the fingertip (BT) and stick length (ℓ) was used to divide 14 subjects (ages 19-21 years) into "novices" (12/14 with a mean BT $\geq$ 300s for 25 consecutive balancing trials for $\ell = 0.56$m after 9 days of supervised practice **of duration** 20-30 minutes per day) and "experts" (2/14 who in addition had a maximum BT $\geq$ 240s when $\ell = 0.3$m determined from five trials after more than 30 days of practice [2]). For the experts the maximum BT obtained for a 0.56m stick was $>$ 1200s.

Stick balancing

The sticks are wooden dowels with a diameter of 6.35mm. Subjects were seated in a chair and were required to keep their back against the chair at all times while facing a blank black screen. Reflective markers were attached to each end of the stick. A high-speed motion capture system (3 Qualisys Oqus 300 cameras, 500-1000Hz) was used to measure the position of the reflective markers.

Data analysis

The change in speed of the fingertip (m/s), ΔV, in one time step Δt provides an estimate of how fast the hand can respond to changes in stick position and was calculated as $\Delta \mathrm{V}(t) = V(t + \Delta t) - V(t)$ where $V(t) = \Delta d(t)/\Delta t$ and $\Delta d(t)$ is the change in the position of the bottom marker in one time step. The quantity ΔV provides an estimate of how fast the hand can respond to changes in stick position and has been demonstrated previously to be Lévy-distributed for skilled novices [4, 7]. The Lévy stable distribution with index α is

$$L_\alpha(\Delta \mathrm{V}, \Delta t) = \frac{1}{\pi} \int_0^\infty \exp(-\gamma \Delta t q^\alpha) \cos(q \Delta \mathrm{V}) dq.$$

where γ is a scaling factor. A normal distribution corresponds to $\alpha = 2$. The data were fit to a Lévy distribution using a MATLAB software package [8]. Distributions were calculated using $> 10^5$ data points.

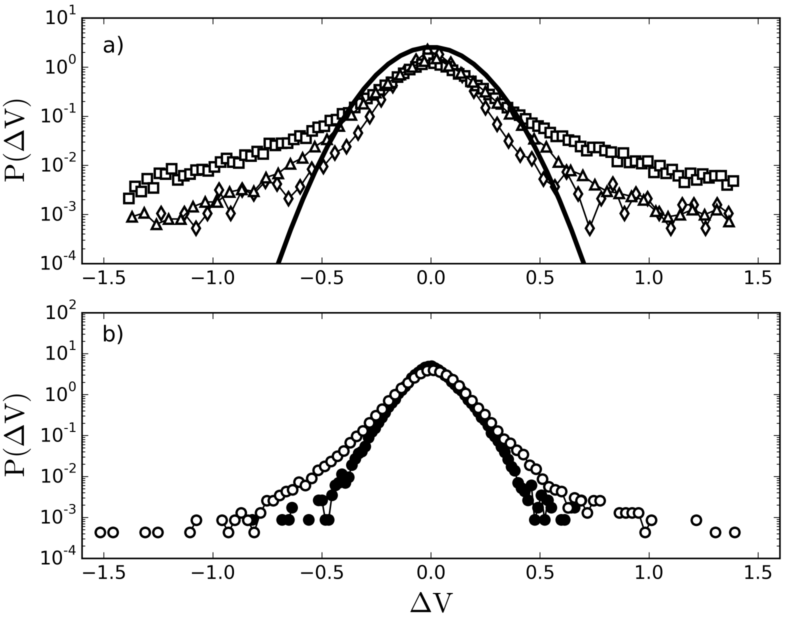

Figure 1: a) The probability distribution, $P(\Delta\mathrm{V})$, for balancing a 0.56m stick as a function of days of practice for a typical skilled novice. ○: 3 days practice (BT = 34s) **JOHN: I cannot see any ○ symbol in panel a) but I see ◇ symbols**, □: 6 days practice (BT = 100s), △: 9 days practice (BT = 300s). The **solid** line is a normal distribution ($\alpha = 2.0$) with same variance as Day 9. b) $P(\Delta\mathrm{V})$ for an expert balancing a 0.56m stick (●: BT $>$ 1200s) and a 0.26m stick (○: BT = 79s). The data for 0.56m is well fit with a normal distribution (line not shown).

Results

Figure 1a show that for a typical skilled novice the distribution for $\mathrm{P}(\Delta\mathrm{V})$ has longer tails than expected for a normal distribution with the same variance (α is 1.8, 1.5, 1.7, respectively, for 3, 6, 9 days of practice). For the expert, α is 1.9 and $\mathrm{P}(\Delta\mathrm{V})$ is well approximated by a normal distribution. Increasing the difficulty of the balance task by shortening ℓ, broadens $\mathrm{P}(\Delta\mathrm{V})$ and lowers α to 1.8. The risk of stick falling is inversely proportional to the BT and hence in this group of subjects is lowest for the expert balancing the 0.56m stick and increases for subjects of lower skill and those balancing shorter sticks. In other words, when the balance task is more difficult, $\mathrm{P}(\Delta\mathrm{V})$ has longer tails.

Discussion

These observations show that a $\mathrm{P}(\Delta\mathrm{V})$ with “long tails” arises in situations in which the risk of stick falling is high. Although both novices and experts use control mechanisms that are tuned towards the edge of stability [2, 4, 5], the nature of these mechanisms for balance control is different: novices likely use delayed state feedback that is directly related to the delayed values of the position, velocity and acceleration [4] whereas experts use a predictor feedback that incorporates an internal model to compensate for the delay by predicting the sensory consequences of the stick's movements [2]. The generation of larger $\Delta\mathrm{V}$ as balance control is threatened likely arises from the interplay between a number of factors including the presence of sensory dead zones in the detection of the vertical displacement angle, the microchaotic nature of the dynamics which arise from the interplay between the dead zone and time-delayed feedback and stochastic uncertainties in the control gains at the edge of stability.

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