TOWARDS UNDERSTANDING HUMAN BALANCE - ANALYZING STICK BALANCING

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In this study stick balancing serves as a role model for more demanding balancing tasks. The purpose is to detect the movement parameters important for stick balancing and their interrelations. Two tilt angles were defined and the relations with the stick coordinates and their derivations analyzed. The correlation between tilt angle and acceleration of the lower coordinate, the angular velocity and the same acceleration of the lower coordinate proved to be the most important relations. The relations were identified to serve as a guideline for establishing a computer simulation of stick balancing which is presented in a separate study. Four parameters were identified and the values determined for comparison with the results of a computer simulation.

Keywords: balancing, movement pattern, motion analysis, stability, correlations, Fourier analysis

INTRODUCTION: Balance is an ability to maintain the center of gravity of a body within the base of support with minimal postural sway (Shumway-Cook, Anson et al. 1988). It is an essential feature for achievement in most human movement tasks. The understanding of movement strategies and the mechanism behind human motion, if in sports or otherwise is of great importance. Good balance ensures top performance for example in gymnastics; it also avoids falling in human gait. Stick balancing represents a classical example for balancing. Cabrera and Milton, between 2002 and 2009, published a series of papers on different aspects of balance using this example. On-off intermittency and parametric noise was the topic of Cabrera and Milton (2002). Milton, Townsend et al. (2009) published a paper where the role of feedback strategies to maintain balance was the focus. Balance and human balance in specific is a topic with a multitude of aspects, and we are far from having a far reaching knowledge. Our long-term strategy of raising our understanding of balance is to develop a computer simulation and compare its results with measurements. Computer models depend on underlying rules that govern the simulation. Therefore, if the predictions and the measurements are in agreement, the underlying rules have a high probability to be valid. In a first attempt we seek some data from stick balancing and moreover its interrelations. To accelerate the developing process of the simulation we looked at data already available. The main task, depicted in this paper, was to analyse the data and identify the underlying relations between the stick's movement and the subjects' action/reaction. This subject-stick interplay mechanism is an important part in a computer simulation. The question was "What must happen for a subject to react?" We expected a deviation from the stick's upright position to trigger a reaction. Also, the stick's angular velocity might provoke the subjects' response. A subject's reaction must result in an accelerated movement of the finger respectively the lower end of the stick. We decided to look into the interplay of the parameters tilt angles (see Figure 1) and coordinate of the lower end of the stick, as well as into the combination of the first and the second derivatives of these parameters. Finally we identified four parameters, which can be used to compare measured data and simulation results.

METHODS: The experimental data were taken from a students' project. A stick (about 1 m of length) had to be balanced on the finger tip for one minute. Two active LED markers of a 3D Lukotronic digitizing system were glued onto the lower part of a stick at a distance of 0.328±0.001 m of each other. Nine sports students (7 males and 2 females) performed the task of balancing the stick for one minute. They repeated the task five times in sequence with short breaks of one to two minutes. The mass of the stick was not determined but this does not compromise the data, since within the equation of motion developed for the computer simulation (separate study) mass is not a parameter. We defined two tilt angles as in Figure

1 and equation (1.1). Tilt angles and derivatives of angles and coordinates were calculated from the raw data. Thereafter, each parameter was filtered using the low pass triple F filter (Vieten 2004). Before a residual analysis (Winter 2005) was performed to find the appropriate cut-off parameter. A correlation matrix was calculated containing the tilt angles, its derivatives angular velocity and angular acceleration and the stick's lower end coordinate

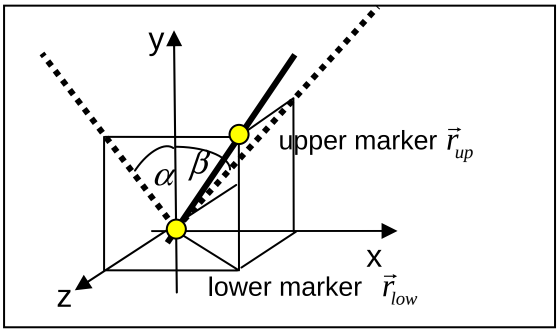

Figure 1: Experimental setup and marker placement

$$\alpha = \arctan\left(\frac{z_{up} - z_{low}}{y_{up} - y_{low}}\right) = \arctan\left(\frac{z}{y}\right)$$
$$\beta = \arctan\left(\frac{x_{up} - x_{low}}{y_{up} - y_{low}}\right) = \arctan\left(\frac{x}{y}\right) \qquad (1.1)$$

as well as its velocity and acceleration. Cross-correlations were performed between the tilt angles and the stick's horizontal acceleration as well as between angular velocities and the stick's acceleration. We determined t_{shift}, the time lag for the highest correlation coefficient r to occur. For comparison between measured data and simulation results we chose the four parameters: 1. $|\overline{\beta}|$, the average of maximal $|\beta|$ at the vertical reversal points (all maxima with $|\beta| \geq 1°$ were included). 2. Correlation coefficient between α respectively β and its horizontal stick acceleration. 3. t_{shift}. 4. The frequency expectation as given in equation (1.2)

$$\langle \nu \rangle = \int_0^{\nu_s/2} \nu \cdot |F(\nu)| \cdot d\nu \bigg/ \int_0^{\nu_s/2} |F(\nu)| \cdot d\nu \qquad (1.2)$$

Here is ν the frequency, ν_s the sampling frequency, and $F(\nu)$ the Fourier transform of α respectively β.

RESULTS:

We calculated the cutoff frequency for the low pass F³ filter to 10 Hz. All secondary parameters (angles and derivations) were calculated first, and then filtered. The average absolute value of the tilt angles at the reversal points averaged for all participants is 2.81° for

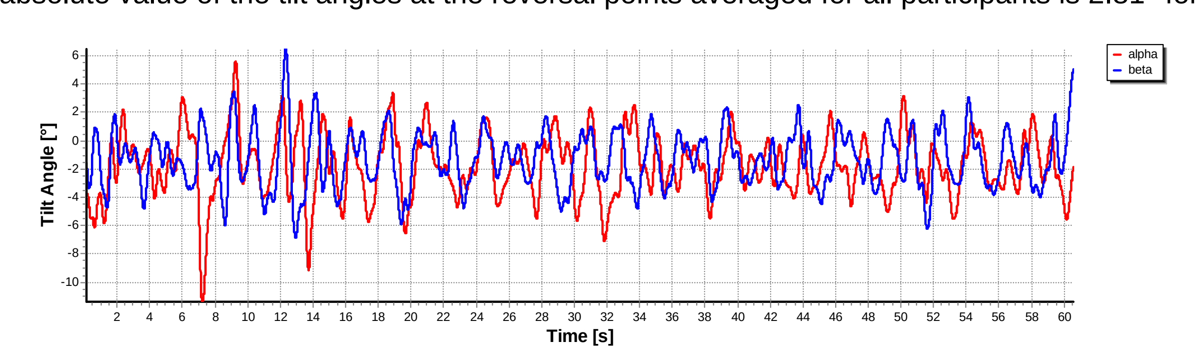

Figure 2: 60 seconds of the two tilt angles of a balancing task of one subject.

α with a standard deviation of ±1.81° and for β it is 2.38°±1.41°. A typical curve of α and β is depicted in **Error! Reference source not found.**.The correlation matrix between the tilt angles, lower marker coordinates and their derivatives for the subject CH4 are displayed in Table 1. The average

Table 1: Correlations between angles, coordinates and its derivatives (p<0.001) for the same subject and task as displayed in Figure 2. n.s. denote non significant results.

Subject CH4	alpha	d(alpha)/dt	d²(alpha)/dt²	beta	d(beta)/dt	d²(beta)/dt²
alpha	1.000	n.s.	-0.467	0.067	-0.048	n.s.
d(alpha)/dt	n.s.	1.000	n.s.	0.051	-0.031	n.s.
d²(alpha)/dt²	-0.467	n.s.	1.000	n.s.	-0.031	-0.244
beta	0.067	0.051	n.s.	1.000	n.s	-0.339
d(beta)/dt	-0.048	-0.031	-0.031	n.s.	1.000	n.s.
d²(beta)/dt²	n.s.	n.s.	-0.244	-0.339	n.s	1.000
x_low	0.050	-0.047	n.s.	-0.525	-0.038	0.090
d(x_low)/dt	0.119	n.s.	n.s.	n.s.	-0.869	n.s.
d²(x_low)/dt²	n.s.	n.s.	0.199	0.645	n.s	-0.747
y_low	-0.081	0.036	0.069	0.022	0.026	n.s.
d(y_low)/dt	-0.085	-0.394	0.197	-0.060	0.154	-0.064
d²(y_low)/dt²	0.125	-0.161	-0.253	-0.062	0.064	n.s.
z_low	-0.511	n.s.	0.099	n.s.	0.041	0.021
d(z_low)/dt	n.s.	-0.783	n.s.	-0.116	-0.029	n.s.
d²(z_low)/dt²	0.717	n.s.	-0.932	0.022	n.s	0.080

value of the correlation $\beta \,\square\, \ddot{x}_{low}$ for all subjects is 0.53±0.09. The cross-correlation between the angular velocity $\dot{\beta}$ of the tilt angle β and the respective acceleration of the lower coordinate $\ddot{z}_{low}$ are shown in Figure 3. The results for $\dot{\alpha}$ are skipped because they resemble

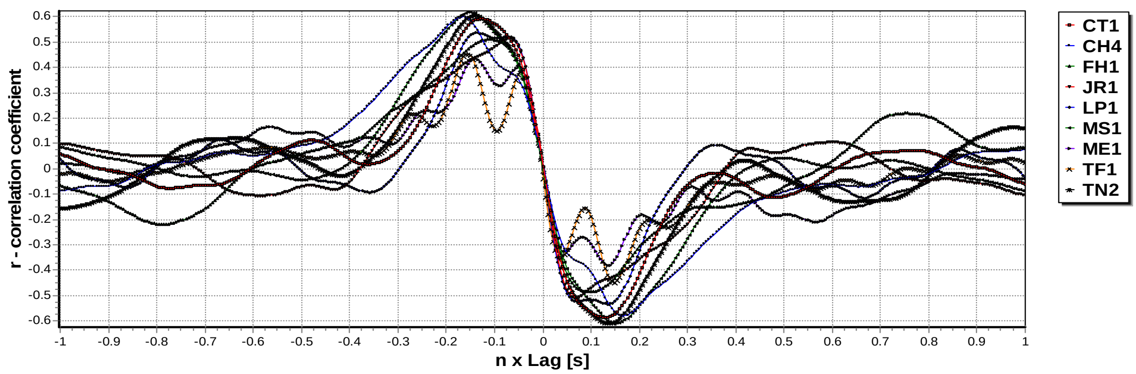

Figure 3: Cross-correlations $\dot{\beta} \,\square\, \ddot{x}_{low}$ for the subjects labeled CT1 to TN2

very much to those received for $\dot{\beta}$. Cross-correlation analysis reveals a high correlation up to r = ± 0.6 for time shifted data in the range of ±0.1 to ±0.2 seconds. The mean shift time (n x Lag [s]) averaged over all subjects is 0.13±0.03 seconds. The expectation value (1.2) averaged over all the subjects is 7.82±3.32 Hz.

DISCUSSION:

Table 1 shows the correlations between tilt angles, lower marker coordinate and its derivatives for one subject. The actual results naturally vary between subjects but the magnitudes do not. A low but statistically significant correlation between $\ddot{\alpha}$ and $\ddot{\beta}$ indicates that the movement activation in x-direction has a moderate effect on the activation in z-direction. Also, it is a hallmark of the stick falling in an arbitrary direction and is not always in alignment with either x- or z-axis. The medium to high correlations between α and z as well as β and x and the relation between their first and second derivatives are just a reminder of their functional relationship and for this reason do not give much insight. A similar argument can be given for correlations between the tilt angles and the vertical component. However, it seems possible that subjects' different strategies to maintain the equilibrium are mildly reflected in the stick's change of the vertical coordinate. Fundamental are the strong correlations $\alpha \square \ddot{z}$ and $\beta \square \ddot{x}$ that are strongest for zero time shift. This is a direct indication of an immediate action once a deviation from the upright position occurs. Taking into account the human reaction time from receiving a stimulus to muscular enervation in the order of 0.1 to 0.2 seconds, anticipation must compensate for the reaction time. $\dot{\alpha} \square \ddot{z}$ and $\dot{\beta} \square \ddot{x}$ show significant correlation only after a time shift coinciding with the human reaction time.

CONCLUSION: The values of the maximal tilt angles show the magnitude of the deviations tolerable before the stick turns over. The most remarkable results however are that in order to control the stick, the angle as well as the angular velocity play substantial roles in a controlling strategy. Further more; we pinpointed the four parameters adequate for a comparison between measured data and a computer simulation as given in the method section. With these results we are well prepared for the development of a computer simulation of stick balancing. The outcome of such a simulation can be directly compared with the results of this paper. We did this analysis because we see stick balancing as a role model for more complicated tasks. Most balancing tasks important for humans such as standing and walking seem to be of different nature. In stick balancing an external object is balanced and the controlling force is applied from outside the balancing system. In most human balancing tasks however, actuation comes from within the balancing system, the human body. This does not mean we are talking about different classes of balancing tasks! We know from looking at the equations of motion that the force exchange between a balancing system and the outside is responsible for the main part of the controlling. Newton's third law teaches us that any force provokes a counter-force. As a consequence there is no principle difference in applying the force from outside or inside the balance system. Those cases having a much higher degree of freedom are different in the muscular interplay to provide the force exchange with the environment. But, the probability is high to find the same principle reaction type as described in this paper in other balancing systems as well.

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