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Correlated hip motions during quiet standing

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Abstract. Kinematic measurements of two simultaneous coordinates from postural sway during quiet standing were performed employing multiple ultrasonic transducers. The use of accurate acoustic devices was required for the detection of the small random noise displacements. The trajectory in the anteroposterior - mediolateral plane of human chest was measured and compared with the trajectory in anteroposterior direction from the upper and lower body. The latter was statistically analyzed and appeared to be strongly anti-correlated. The anti-correlations represent strong evidence for the dominance of hip strategy during an unperturbed one minute stance. That the hip strategy, normally observed for large amplitude motions, also appears in the small amplitude of a quite stance, indicates the utility of such noise measurements for exploring the biomechanics of human balance.

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1. Introduction

Physical investigations into the motor control of body motions have traditionally been of three types (Shumway-Cook and Wallacot 1995): (i) direct muscle tension measurements, (ii) kinetic analysis of forces, and (iii) kinematic analysis of body displacements. The experimental techniques used to study body motions reflect the requirements of the above types of investigation. For example, electromyography has been the technique most often used to monitor the activity of muscles (Granley 1984, Winter 1990, Perry *et al* 1981). Electrodes are placed on the skin above the particular muscles of interest. Force transducers and force plates measure the ground body reaction forces to body movements (Prietro *et al* 1993, Firsov *et al* 1993, Winter 1990, Goldie *et al* 1989).

In the present work, purely kinematic studies of body motions will be of interest. Previous studies have employed electrical potentiometers to measure joint angles in those cases for which angular increments induce voltage differences (Barlett *et al* 1986, Campbell *et al* 1989). Accelerometers have been constructed from force transducers which also (ultimately) depend on kinematic induced voltages (Thomas and Whitney 1959). Finally, video, cinematography and optoelectric systems have been used to form images of body motions. The optoelectric systems require that infrared sources

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and/or reflectors be worn on each anatomic landmark to be imaged (Whittle 1991, Winter 1990).

Kinematic experimental methods have probed a well known set of strategies that are used by humans to maintain balance (Nasher 1985). The strategies involve the ankles, the hips and stepping. These three forms of motion are exhibited in various degrees depending on the nature of the motor task.

The purpose of this work is to introduce a new ultrasonic sound wave assessment (SWA) device which aids the analysis of body movement kinematics. The SWA device measures the coordinates X_1, X_2, \dots of anatomic landmarks as a function of time. This device has been employed to investigate balance strategies during quiet standing. Surprising but unambiguous experimental results show that strongly correlated hip motions play a central role even in the postural sway of an *unperturbed stance*. This experimental result was made possible due to the accuracy of the SWA device.

In Sec.2, the SWA device will be described in detail. In Sec.3, two coordinate measurements are discussed. The measurements involve the random noise motions of quietly standing subjects. Two coordinates were selected so as to emphasize the hip strategy. The observed restricted motions in the two coordinate phase space indicated the dominance of the hip strategy in the quiet postural stance. In Sec.4 we calculate the correlation functions for the two coordinate phase space and deduce that the hip motions are quite strongly correlated in *all of the subjects* measured. In the concluding Sec.5, previous notions of quiet standing balance strategies will be discussed in the light of presently reported data.

2. Sound wave assessment device

The SWA device consists of an even number of small ultrasonic transducers. The measurement of \mathcal{N} coordinates requires $2\mathcal{N}$ transducers. Each of the \mathcal{N} *pairs* of transducers send ultrasonic pulses to one another at a rate of 1800 pulses per minute. One transducer of each pair is positioned on a stable laboratory stand. The other transducer of the pair is attached to a quietly standing subject. Each pulse sent by one transducer in a given pair is later detected by the other transducer in the same given pair. The distance between the two transducers of a given pair can then be obtained from the time required for the pulses to travel from the sender to the receiver. Thus, each pair of transducers measures one coordinate function $X(t)$, i.e. the distance between the pair of transducers at time t .

In the photography industry, a single ultrasonic transducer system has been used to measure the distance between the camera lens and the object to be photographed. Twice the distance is computed from the measured pulse emission time and the measured pulse detection time at which the transducer detects its own echo. Our use of *transducer pairs* improves the accuracy of the coordinate measurement system by having less air absorption as well as less spatial dispersion (fanning out) of the ultrasound signals.

Each ‘‘pulse’’ (produced at the rate of 1800 per minute) in reality consists of 16 very closely spaced pulses separated by time intervals of $\delta t \approx 2 \times 10^{-5}$ sec. If a transducer pair is well aligned, then first pulse of the sixteen sub-pulses will be detected. If the transducer pair alignment is somewhat skewed, then the second sub-pulse will be detected. The coordinate displacements are measured to within 0.02 cm in a pulse bandwidth of ~ 12 kHz. This yields a displacement noise error of $\delta X \sim 2 (\mu m / \sqrt{Hz})$.

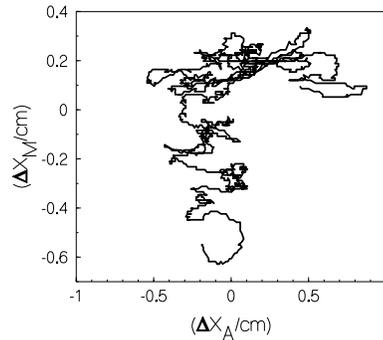


Figure 1. A measured quiet standing upper body random meandering path in the plane of the anteroposterior coordinate X_A and mediolateral coordinate X_M is plotted. The observation time is one minute.

Thus, we can record the fine displacements of a subject’s body coordinates $X_1(t), X_2(t), \dots$ as a function of time. Twelve healthy subjects in the age range between 15 and 65 years of age participated in this study.

3. Measured paths in two coordinate planes

Shown in Fig.1 is the random motion in the (X_A, X_M) plane of a subject’s upper body motion during quiet standing. The coordinate X_A measures the subject’s upper body anteroposterior displacement, i.e. the forward and backward motions of the transducer attached to the subject’s back. The coordinate X_M measures the upper body mediolateral displacement, i.e. the side to side motions of the transducer attached to the subject’s shoulder. The random motions were measured over a time period of one minute. The quantities $\Delta X_A = X_A - \bar{X}_A$ and $\Delta X_M = X_M - \bar{X}_M$ denote the deviations from the mean taken over the observation time. One notes the meandering nature of the noise in the (X_A, X_M) plane.

By contrast, in Fig.2, we consider the one minute measurement (on the same subject) in the (X_U, X_L) plane with *both displacements* in the anteroposterior direction. The coordinate $X_U = X_A$ was again measured from a transducer attached to the subject’s back (upper body) while the coordinate X_L was measured from a transducer attached to the back of the subjects thigh slightly below the hip (lower body). The deviations from the mean are $\Delta X_U = X_U - \bar{X}_U$ and $\Delta X_L = X_L - \bar{X}_L$. One notes the very constrained nature of the noise in the (X_U, X_L) plane. The coordinates X_U are highly correlated. The positions in the plane are nearly *collinear*, as shown in Fig.2 along with a “best fit” line.

In Fig.3, we plot both coordinates $X_U(t)$ and $X_L(t)$ as a function of time for an observation time of one minute. If one views only one of the coordinates, then the motion appears to be random. However when one views both coordinates, the changes in $X_U(t)$ and $X_L(t)$ are seen to be strongly anti-correlated. When one of the coordinates increases, the other coordinate decreases in proportionate amounts. Thus,

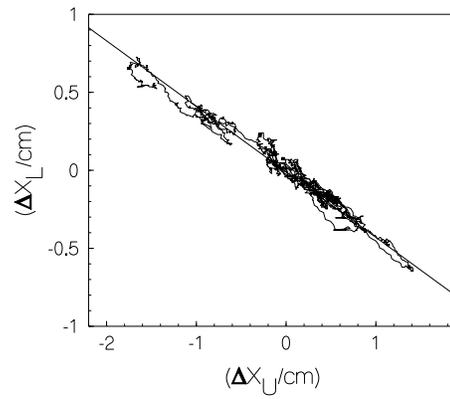


Figure 2. A measured quiet standing highly correlated path in the plane of the upper body coordinate X_U and lower body coordinate X_L is plotted. The observation time is one minute. That the random path is almost *collinear* in the (X_U, X_L) plane is evidence of the highly collective nature of the dominating hip strategy.

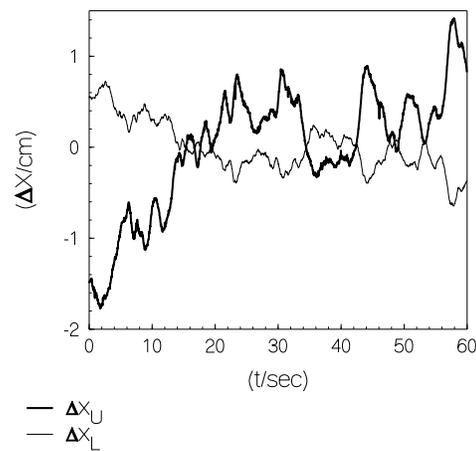


Figure 3. Shown are plots of the two coordinates $X_U(t)$ and $X_L(t)$ as functions of time. This data was used to determine the path in Fig.2. One notes the strong anti-correlation between the coordinates. When $X_U(t)$ is increasing, $X_L(t)$ is decreasing in proportionate amounts, and vice versa.

when the upper body moves forward, the lower body moves backward and vice versa. This describes precisely the hip balance strategy.

4. Statistical analysis

A quantitative statistical formulation of the anti-correlated kinematics of the hip strategy may be formulated as follows (Martin 1967): (i) For a given subject, the time averaged coordinate correlation matrix elements may be defined as

$$\mathcal{G}_{UU} = \frac{1}{\tau} \int_0^\tau \Delta X_U(t) \Delta X_U(t) dt, \quad (1)$$

$$\mathcal{G}_{LL} = \frac{1}{\tau} \int_0^\tau \Delta X_L(t) \Delta X_L(t) dt, \quad (2)$$

$$\mathcal{G}_{UL} = \mathcal{G}_{LU} = \frac{1}{\tau} \int_0^\tau \Delta X_U(t) \Delta X_L(t) dt, \quad (3)$$

where $\tau = 60 \text{ sec}$ is the observation time. (ii) The normalized cross correlation is defined

$$\mathcal{C}_{UL} = \frac{\mathcal{G}_{UL}}{(\mathcal{G}_{LL}\mathcal{G}_{UU})^{1/2}}, \quad (4)$$

which obeys the inequalities $-1 \leq \mathcal{C}_{UL} \leq +1$. The extreme of the inequality $+1$ indicates perfect correlation, -1 indicates perfect anti-correlation and 0 indicates lack of any correlation.

All of the measured subjects exhibited a cross correlation function in the range $0.89 \leq (-\mathcal{C}_{UL}) \leq 0.99$ indicating an almost perfect anti-correlation. For the totality of the experimental data, one may define the ensemble average of the correlation matrix elements for $N = 12$ subjects

$$\bar{\mathcal{G}}_{ab} = \frac{1}{N} \sum_{j=1}^N \mathcal{G}_{ab}^{(j)}, \quad \text{where } a = U, L, \quad b = U, L, \quad (5)$$

and the ensemble total cross correlation

$$\bar{\mathcal{C}}_{UL} = \frac{\bar{\mathcal{G}}_{UL}}{(\bar{\mathcal{G}}_{LL}\bar{\mathcal{G}}_{UU})^{1/2}}. \quad (6)$$

For the totality of the experimental data from all of the subjects we find $\bar{\mathcal{C}}_{UL} = -0.92$ almost completely anti-correlated.

The above statistical analysis verifies objectively and quantitatively the view expressed in Sec.3. The hip strategy consists of a motion wherein the upper body and lower body randomly oscillate but in proportionately opposite directions.

5. Discussion

In the study of condensed matter statistical mechanics, it is well known that one may tease out of the thermal equilibrium noise data many important mechanical parameters (Martin 1967). These parameters normally enter into the large dynamical displacements that would be present were those systems to be externally driven. Similarly, the notion has appeared in the literature that it would be possible to learn much about non-equilibrium motor biomechanics by merely observing the small

displacement noise noise during quite standing (Lauk *et al* 1998). This view certainly turns out to be true for the hip strategy employed to keep ones balance, as shown from the data reported here.

Non-equilibrium hip motions are evident, for example, to those who have observed an infant in that time interval *after* knowing how to crawl but *before* learning how to walk (Shumway-Cook 1995). When *not* very quietly standing, the infant exhibits large hip motions while trying to stand. Since (during this critical period in life) the transition rate Γ for a fall (Koleva *et al* 1999) obeys $\Gamma > 0.05 \text{ Hz}$, the infant often falls when the upper body coordinate is positive, either by sitting (backward fall) or returning to a crawl (forward fall). The non-equilibrium hip motions are equally evident in adults trying to balance on a tight rope with their forward direction normal to the tight rope direction. Since normal (non-circus trained) adults have a tight rope transition rate for a fall which also obeys $\Gamma > 0.05 \text{ Hz}$, the large hip strategy motions are clearly seen to exist somewhat before the inevitable fall onto a safety net.

What has been shown in this work, is that the hip strategy motions are clearly in operation during a quite stance, *even though the amplitude of hip motions are too small to observed by the unaided eye*. With the aid of the ultrasound transducers in the SWA device, the two coordinate measurements clearly show an ongoing hip strategy in each and every subject tested. By a judicious choice of coordinates, other strategies should also yield to a quiet standing noise analysis technique.

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