DETECTION OF THE CRITICAL POINT INTERVAL OF POSTURAL CONTROL STRATEGY USING WAVELET TRANSFORM ANALYSIS

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Abstract: Postural balance is often studied in order to understand the effect of sensory degradation with age. The aim of this study was to develop a new method of detecting the critical point interval (CPI) at which sensory feedback is used as part of a closed-loop postural control strategy. Postural balance was evaluated using centre of pressure (COP) displacements measured using a force plate for 17 control subjects and 10 elderly subjects under control (eyes open) and experimental (eyes closed, vibration) conditions. A modified local-maximum-modulus wavelet transform analysis using the power spectrum of COP signals was used to calculate the critical point when closed-loop control occurs. Lower values of CPI are associated with increased closed-loop postural control, indicating a quicker response to sensory input. This strategy of postural control will require greater energy expenditure due to the repeated muscular interventions in order to remain stable. The CPI for elderly subjects occurred significantly quicker than for control subjects, indicating that posture was more closely controlled. Similar results were observed for eyes closed and vibration conditions. The CPI parameter offers a new method of detecting differences in postural control between different experimental conditions or changes due to ageing.

1 INTRODUCTION

Balance is regularly studied in order to better understand postural control mechanisms. One reason for the interest in balance is its relationship with falls, which are a major problem in the elderly. Indeed, a problem with balance is one of the most commonly-cited risk factors for falls (Rubenstein and Josephson, 2002). Balance is maintained using the visual, vestibular, and proprioceptive systems.

Postural degradations occur with age, and can also be artificially created by impairing one of the sensory systems, for instance by closing a subject’s eyes. The proprioceptive system can also be impaired by applying vibration to the tibialis anterior tendon when subjects are in a static upright position, which creates an illusion of body inclination, thus decreasing postural stability and increasing postural sway (Roll and Vedel, 1982).

Balance can be measured either clinically, or biomechanically, for which force-plate analysis is often used. A range of different parameters can be extracted from the centre of pressure (COP) obtained from the force plate, including temporal and spectral parameters, as well as those related to the organisation of the trajectory of the COP. Pioneering work in this area was performed by Collins and De Luca (Collins and De Luca, 1994), who hypothesised that upright stance was controlled by open-loop and closed-loop strategies, which correspond to posture control strategies without and with sensory input, respectively. In the case of an open-loop control, sensory feedback is not used, whereas closed-loop control uses feedback from the proprioceptive, vestibular, or visual systems to maintain an upright stance. Collins and De Luca identified the critical point at which open-loop and closed-loop control strategies diverged, and proposed a method by which this time could be calculated (Collins and De Luca, 1994). Although the proposed method is based on posture control strategies, the method used to calculate the critical time interval makes assumptions that the two points used to fit the regression lines to the data occur

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between one second and 2.5 seconds (Collins and De Luca, 1994).

The present paper describes a new method that can be used to calculate the time at which a change is made between open and closed loop control strategies. The proposed method, based on wavelet analysis will be used to calculate the critical point interval of the COP signal for elderly and control subjects, as well as for eyes closed and vibration conditions.

2 METHODS

2.1 Subjects

Seventeen healthy control subjects and ten healthy elderly subjects (4 males and 6 females) participated in the study. Control subjects' mean age, height and weight were 33.3 ± 7.4y, 168.0 ± 6.5cm, and 65.7 ± 17.6kg, respectively. Elderly subjects' mean age, height and weight were 80.5 ± 4.7y, 165.6 ± 7.0cm, and 71.9 ± 9.9kg, respectively. All subjects who participated gave their written informed consent. No subjects reported any previous musculoskeletal dysfunction.

2.2 Centre of Pressure Data

Centre of pressure data were recorded using a Bertec 4060-08 force plate (Bertec Corporation, Columbus, OH, USA), which amplifies, filters, and digitises the raw signals from the strain gauge amplifiers inside the force plate. The resulting output is a six-channel 16-bit digital signal containing the forces and moments in the x, y, and z axes. The digital signals were subsequently converted via an external analogue amplifier (AM6501, Bertec Corporation).

The coordinates of the COP signals can be calculated as follows:

$$X = AP = \frac{M_y}{F_z}\ ;\ Y = ML = \frac{M_x}{F_z} \qquad (1)$$

The initial COP signals were calculated with respect to the centre of the force-plate before normalisation by subtraction of the mean.

2.3 Data Acquisition and Processing

Data were recorded using the ProTags™ software package (Jean-Yves Hogrel, Institut de Myologie, Paris, France) developed in Labview® (National Instruments Corporation, Austin TX, USA). Data were sampled at 100 Hz, with an 8th-order low-pass Butterworth filter with a cut-off frequency of 10 Hz. All calculations of COP data were performed with Matlab® (Mathworks Inc, Natick, MA, USA).

2.4 Experimental Protocol

Subjects were tested using two experimental protocols with a Bertec 4060-80 force plate (Bertec Corporation, Colombus, OH, USA). Elderly subjects were tested with their eyes open, while control subjects were tested with their eyes open, their eyes closed, as well as with vibration (eyes closed).

For the vibration condition, vibration was applied bilaterally using the VB115 vibrator (Techno Concept, Cereste, France) to the tibialis anterior tendon for 10 s at 50, 70, and 90 Hz. Immediately after vibration, subjects were instructed to step onto the force plate, in order to ensure subjects were subjected to the post-vibratory response.

After 12 s standing on the force plate, a second verbal command was given for subjects to step down backwards. Subjects remained as still as possible with their arms placed at their sides throughout the protocol, while no constraint was given over foot position, with subjects tested barefoot. Measurements were repeated five times for each experimental condition, with 30 s between each test.

2.5 Identifying the Critical Point using Wavelet Transform Analysis

2.5.1 Locating the Critical Point

The critical point is defined as the point at which sway is controlled by the closed-loop (feedback) system. When postural control changes from open-loop to closed-loop, a local maximum should be observable in the COP. When upright stance is under open-loop control, sway moves toward a certain direction reaching a local maximum, at which point commands from the closed-loop system pull sway away from the local maximum back to the equilibrium position (Figure 1).

It has been shown that local maximum modulus wavelet transform analysis is well-suited to the detection of local maxima (Mallat and Hwang, 1992). The method used in the present study differs only in that the power spectrum is used rather than the modulus, as the power spectrum represents the energy in sway.

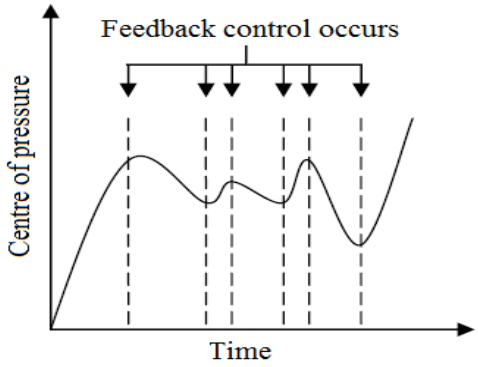

Figure 1: Feedback control and the local maxima of the centre of pressure signal over time. Data are in arbitrary units.

2.5.2 Wavelet Function and Frequency Bands

The wavelet transform method is particularly suitable for analyzing non-stationary signals in a multi-scale manner by varying the scale coefficient that represents frequency.

The wavelet transform formula is:

$$WT(a,b) = |a|^{-1/2} \int f(t)\varphi\left(\frac{t-b}{a}\right)dt \qquad (2)$$

where b is the translation parameter and a is the scale (frequency), and $WT(a,b)$ is the wavelet coefficient.

The power spectrum $PS(a,b)$ is defined as

$$PS(a,b) = |WT(a,b)|^2 \qquad (3)$$

The wavelet function $\varphi(x)$ should satisfy a number of constraints, including zero mean and orthogonality (Muzzy et al., 1991). Some wavelet functions are known to distort low frequency components. In order to avoid this problem, Coiflets wavelet functions were used.

The sway energy of COP signals has been shown to be concentrated below 2 Hz (Ferdjallah et al., 1999), with the principal COP energy being distributed in the range of 0.1-0.5 Hz (Schmuckler, 1997, Loughlin et al., 1996). Preliminary findings from the present study showed that most of sway energy was less than 0.5 Hz, as shown in Figure 2.

For the wavelet function $\varphi(x)$, scale a determines the frequency and b determines the translation. In the present study, a was chosen to force the frequency of wavelet transformation to the range of 0.1-2.0 Hz.

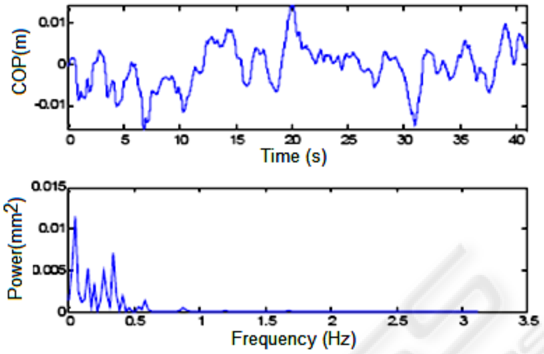

Figure 2: Sample power spectrum of COP data (AP direction).

The 0.1-2.0 Hz frequency band can be divided into sub sections for which different control systems are thought to be involved. For instance, Diener and Gagey suggested that the visual system dominates frequency bands below 0.5 Hz (Diener et al., 1984, Gagey et al., 1985). In contrast, Thurner and colleagues reported that the visual system operates in the range of 0-0.1 Hz, the vestibular system from 0.1-0.5 Hz, somatosensory activity from 0.5-1.0 Hz, while sway over 1.0 Hz is directly controlled by the central nervous system (Thurner et al., 2000). Based on these findings, the frequencies of 0.5-1.0 Hz were chosen for the present study as the zone in which proprioceptive input predominates.

The relation between scale and frequency can be shown as:

$$F_a = \frac{F_C}{a.P} \qquad (4)$$

Where F_c is the centre frequency, F_a the frequency for scale a, and P is the sampling period (0.01 s).

It is evident that the scale a should be in the range 0.5-1.0 Hz for the present study, given the use of proprioceptive perturbations. To this end, a is transformed using a base-2 logarithm, and thereafter denoted as the new scale s. The lower and upper bounds of scale s were chosen as 6.5 and 8, respectively. This scale range corresponds to the frequency bands in the range of [0.44, 0.88] Hz. After determining scale s, translation b, and the wavelet function, the power spectrum can be calculated, an example of which is shown in Figure 3.

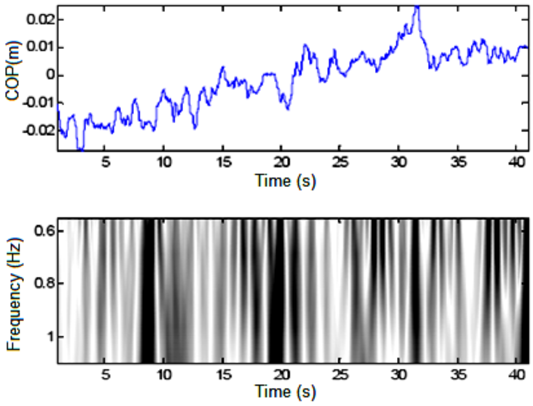

Figure 3: Sample wavelet power spectrum of COP data (ML direction). Darker and lighter areas represent larger positive and negative power spectrum values, respectively.

2.5.3 Identifying the Critical Point Time Interval

Postural control strategies can be changed from open-loop control to closed-loop in which visual, vestibular and somatosensory feedbacks can be used. When feedback control is used, sway moves away from the local maximum and back to the equilibrium position. The critical point occurs at scale *s* and time *t*, where the power spectrum is at the local maximum. It is simply the local maximum of the power spectrum wavelet transform method (LMPS), which can be mathematically defined as:

$$PS(s,x) < PS(s,x_0) \qquad (5)$$

Where x is either the left or right neighbourhood of x_0, $x \in R$, and *s* is scale.

There are numerous local maxima within specific frequency bands, which indicates that feedback control has been started at time *t* and scale *s*. Postural control corresponds to the frequency bands rather than a single frequency, meaning that the identification of maxima across the frequency range was required. A local maximum line L_t can be defined as the line consisting of the local maxima at time *t* across frequency bands from *a* to *b:*

$$L_t \overset{d}{=} \{PS(s,t), s = a..b\} \qquad (6)$$

In the present study, local maxima lines were identified in the frequency bands [*a*=0.44, *b*=0.88] Hz. It is necessary to search for the local maximum around time *t* within a 2Δ*t* interval denoted by [*t*-Δ*t*, *t*+Δ*t*]. If the local maximum line L_t can be identified within the time interval [*t*-Δ*t*, *t*+Δ*t*], it is concluded that feedback control has been used at time *t*. The time interval Δ*t* used to search for the local maximum line depends on the specific data. If Δ*t* is too small then too many local maxima will be identified. In the present study Δ*t* was chosen as 0.62 s. There are numerous such local maximum lines for each scale. The mean of the length of these local maxima lines was calculated and taken to be the critical point interval (CPI). The average CPI for all five trials for each subject for each experimental condition was used for subsequent statistical analysis.

2.6 Statistical Analysis

All statistical analyses were performed with the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). Analysis of variance was used to compare results between conditions, with CPI as the dependent variable and the experimental condition as the independent variable. Data were expressed as means and 95% confidence intervals. Alpha level was set at p<0.05.

3 RESULTS

The CPI for elderly and control subjects under the eyes open condition are presented in Figure 4. Significantly higher values for CPI can be seen for control subjects than for elderly subjects (p<0.05). The CPI for AP displacement was significantly lower than the corresponding value for ML displacement for both control and elderly subjects alike (Figure 4; p<0.05).

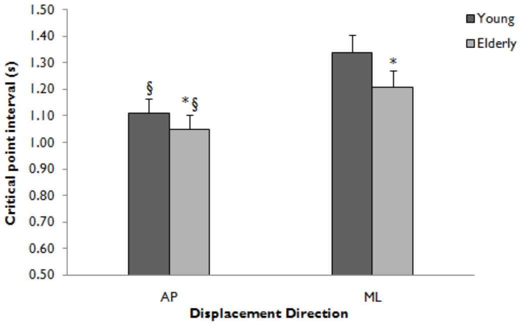

Figure 4: Critical point interval for elderly subjects and control subjects in the eyes open condition. Data are means and 95% confidence intervals. *Significantly different from control subjects (p<0.05); §Significantly different from ML displacement (p<0.05).

The results for the eyes open and eyes closed conditions are presented in Figure 5. Significantly higher values for CPI were observed for the eyes open condition than for eyes closed ($p<0.05$). Significantly lower values of CPI were observed for AP displacement when compared to ML displacement for both eyes open and eyes closed conditions (Figure 5; $p<0.05$).

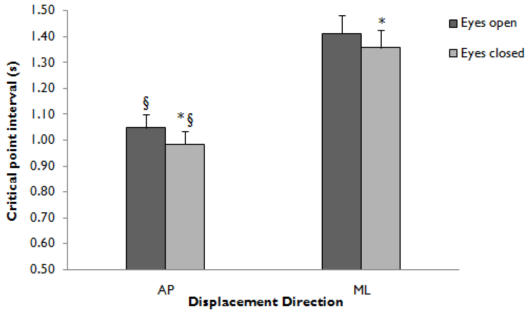

Figure 5: Critical point interval for control subjects in the eyes open and eyes closed conditions. Data are means and 95% confidence intervals. *Significantly different from eyes open ($p<0.05$); §Significantly different from ML displacement ($p<0.05$).

In respect to vibration, there was no significant difference between conditions for ML displacement (Figure 6). In contrast, both 70 Hz and 90 Hz vibrations significantly decreased CPI values in comparison to the 0 Hz and 50 Hz vibration condition (Figure 6; $p<0.05$).

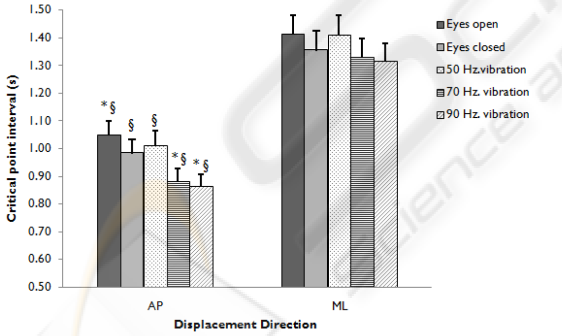

Figure 6: Critical point interval for control subjects in the eyes open, eye close and vibration condition. Data are means and 95% confidence intervals. *Significantly different from eyes closed ($p<0.05$); §Significantly different from ML displacement ($p<0.05$).

4 DISCUSSION

Lower values of CPI are associated with increased closed-loop postural control. In essence, the lower the CPI value, the quicker the response to sensory input, and thus the greater reliance on closed-loop control. Lower values of CPI can therefore be interpreted as a less efficient open-loop control, thus requiring an earlier intervention of the closed-loop system. This strategy of postural control will require greater energy expenditure due to the repeated muscular interventions in order to remain stable.

The CPI parameter proposed in the present paper was able to distinguish between all of the different experimental conditions tested. In respect to differences between AP and ML displacements, CPI values were lower for AP than for ML displacement for all experimental conditions indicating less postural stability. This result was expected given that ML displacement is more stable than AP displacement due to the anatomy of the ankle and knee joints, which limit movement in the ML direction. In addition, subjects' feet are placed in a series position for the ML direction, as opposed to the parallel positioning for AP.

In respect to differences with ageing, elderly subjects had lower CPI values than control subjects for both AP and ML displacement. Such results are indicative of an earlier feedback control for elderly subject, which is due to a tightly controlled posture in elderly subjects, as reported previously for other parameters such as Detrended Fluctuation Analysis (DFA). In studies of DFA, elderly subjects had less complex patterns of AP displacement, which is indicative of a tight postural control used to reduce displacement as much as possible in order to maintain a stable posture (Amoud et al., 2007a, Norris et al., 2005).

The differences observed between eyes open (EO) and eyes closed (EC) conditions were in agreement with those between elderly and control subjects. The CPI values were greater for EO than for EC for both AP and ML displacements. The lack of visual information required subjects to tightly control displacement in both AP and ML directions using the closed-loop system in order to maintain equilibrium.

The effect of the vibration applied to the tibialis anterior tendon is to decrease the stability of the postural control system by invoking an illusion of tilt. The vibration required to invoke this effect must be at least 70 Hz. This effect is only seen in the AP direction in which the tendinous vibration was applied.

The results for all experimental comparisons demonstrate that a decreased ability to maintain postural stability can be identified by an increased use of the closed-loop postural control system. Such results might seem contradictory at first, in that both elderly subjects and subjects with no visual feedback can tightly control their postural equilibrium. However, similar results have been reported for COP signals for a range of parameters such as entropy and DFA (Amoud et al., 2007b, Norris et al., 2005, Amoud et al., 2007a), as well as for other physiological signals such as force production (Challis, 2006). It has also been suggested that physiological control processes become less complex with age as well as when disease is present (Goldberger et al., 2002).

5 CONCLUSIONS

In conclusion, the CPI parameter offers a new method of detecting differences in postural control between different experimental conditions or changes due to ageing. Lower values of CPI reflect greater reliance on closed-loop postural control, which requires greater energy expenditure due to the repeated muscular interventions in order to remain stable.

ACKNOWLEDGEMENTS

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