Is the method of signal analysis and test selection important for measuring standing balance in subjects with persistent whiplash?

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Abstract

Dizziness and or unsteadiness, associated with episodes of loss of balance, are frequent complaints in those suffering from persistent problems following a whiplash injury. Research has been inconclusive with respect to possible aetiology, discriminative tests and analyses used.

The aim of this pilot research was to identify the test conditions and the most appropriate method for the analysis of sway that may differentiate subjects with persistent whiplash associated disorders (WAD) from healthy controls. The six conditions of the Clinical Test for Sensory Interaction in Balance was performed in both comfortable and tandem stance in 20 subjects with persistent WAD compared to 20 control subjects. The analyses were carried out using a traditional method of measurement, total sway distance, to results obtained from the use of wavelet analysis.

Subjects with WAD were significantly less able to complete the tandem stance tests on a firm surface than controls. In comfortable stance, using wavelet analysis, significant differences between subjects with WAD and the control group were evident in total energy of the trace for all test conditions apart from eyes open on the firm surface. In contrast, the results of the analysis using total sway distance revealed no significant differences between groups across all six conditions. Wavelet analysis may be more appropriate for detecting disturbances in balance in whiplash subjects because the technique allows separation of the noise from the underlying systematic effect of sway. These findings will be used to direct future studies on the aetiology of balance disturbances in WAD.

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Dizziness and/or a sensation of unsteadiness are frequent complaints in those suffering problems following a whiplash injury [1]. Our previous research established that 74% of 102 patients with persistent whiplash associated disorders (WAD) [2], described these symptoms, with a sensation of unsteadiness (90%) being the most common description [3]. In addition, some patients also complained of episodes of loss of standing balance (48%) and some of actual falls (21%) [3]. To improve evaluation and rehabilitation of patients following a whiplash injury, it is important to determine whether these reported patient complaints relate to measurable changes in postural control. Although trends towards poor balance are evident in previous studies of patients with persistent WAD, research is inconclusive with respect to the etiology of the balance disturbance. Furthermore, inclusion/exclusion criteria, test selection and methods of analysis have varied between studies and large inter-individual variations have also been demonstrated [1,4–6].

Test selection and method of analysis of balance responses were considered a priority for this initial study before further issues such as etiology of balance disturbances in WAD could be considered. The testing procedure should be standardized to enable comparison with other studies and other conditions, but of sufficient challenge to the postural control system. The analysis of the sway trace should also be appropriate for the data obtained.
In studying balance, computerised dynamic posturography (CDP) is often used. The standard sensory organization test (SOT) uses sway referencing of the visual surround and/or platform so that visual and/or proprioceptive information is rendered orientationally inaccurate [7]. The clinical test for sensory interaction in balance (CTSIB) was developed by Shumway-Cook and Horak [8] as a simplified version of the SOT and consists of six tests which gradually alter the degree of difficulty for balance in bilateral stance [9–11].

An additional challenge to balance can be implemented by altering the subject’s stance position. Comfortable stance is commonly used, although narrow, tandem and unilateral stance has been used in studies of persons with multiple sclerosis and following concussion [12–14]. A recent study by Frozovic [13] found that subjects with multiple sclerosis only had postural deficits in tandem stance. It may also be necessary to challenge the postural control system at this higher level to demonstrate postural disturbances in WAD. Thus both comfortable and tandem stance have been selected for investigation in this study.

Signal analysis may also be important for the differentiation between patients with WAD and healthy control subjects, as well as to distinguish between those patients with and without balance problems. The methods traditionally used to interpret the signal include the total sway distance, centre of gravity exertion, average radial deviation, average absolute velocity of the centre of pressure, frequency analysis and limits of stability of the sway signal [1,4,14,15]. The raw data from the CDP sway trace is a non-stationary signal and fractal in nature. This suggests that the ‘traditional’ mathematical manipulations of the raw data may not be the most appropriate methods of analysis to use for patient groups such as those following a whiplash injury. These techniques only provide average gross global measures of function, eliminating information on the precise nature of changes in sway over time. A more precise measure of the change in sway over time could be gained by using wavelet analysis. Wavelet analysis has been successfully adopted in other medical research in an attempt to provide a measure of the change in sway over time. A more precise measurement of the change in sway over time could be gained by using wavelet analysis. Wavelet analysis has been successfully adopted in other medical research in an attempt to

1. Methods

1.1. Subjects

Twenty subjects with ongoing pain and symptoms associated with a WAD (at least three months post-injury), who reported intermittent symptoms of dizziness and or unsteadiness at least once per week, were admitted to this study along with 20 matched control subjects. Subjects with WAD were recruited from consecutive eligible patients attending the Whiplash Research Unit in the Division of Physiotherapy at The University of Queensland. Exclusion criteria included a reported period of unconsciousness or concurrent head injury with the whiplash injury, pre-existing diagnosed or suspected vestibular pathology, psychiatric conditions, neurologic defects and hip, knee or ankle pathology. Subjects were asked to refrain from taking any medication that may adversely affect postural sway for 24 h prior to testing [20]. The subjects with WAD who entered the study were categorized as WAD II according to the Quebec Task force classification [2] and had symptoms that were not abating. They comprised 15 females and 5 males whose mean age was 32.4 years (range 19–45 years). The mean length of time following injury was 27.2 months (range 4–60 months). Control subjects included 20 subjects (11 females and 9 males) whose mean age was 27.6 years (range 19–45 years) with no history of whiplash, neck pain, headache or dizziness. These subjects were recruited from volunteers who responded to advertising in a local newspaper and on the university campus. Any subject (WAD or control) over the age of 45 years was excluded to minimise the effects of ageing on balance [21]. Ethical clearance for this study was granted from the Medical Ethics Committee of The University of Queensland and all participants provided informed consent.

1.2. Measurements

1.2.1. Computerised posturography (CDP)

A computerised, stable force platform (40 cm × 60 cm) measured postural sway and changes in standing balance under altered visual and support conditions. The ground reaction forces were registered by strain gauges located in each corner of the plate to measure force changes over time in both the medial-lateral (ML) and anterior-posterior (AP) directions. The signals were recorded on a computer and the raw traces were produced both numerically and graphically.

The conditions for the CTSIB [8] were performed with the subject standing in both comfortable and tandem stance. The first three of the six CTSIB conditions were executed on a firm surface. Recordings of sway were made with the eyes open (EOF), eyes closed (ECF) and under visual conflict (VCF), provided by wearing a lightweight paper dome on the head. These three conditions were then repeated on a soft surface: eyes open soft (EOS), eyes closed soft (ECS) and visual conflict soft (VCS) to complete the six conditions. The soft surface was a piece of high-density (10 cm thick) foam rubber.
placed on the platform. The subjects’ feet were repositioned exactly on each surface for every test using a paper traced foot position based on the “comfortable position” described by McIlroy and Maki [22]. In tandem stance, the dominant foot was placed directly behind the non-dominant foot. Leg dominance was defined as the preferred leg to kick a ball [14,23].

1.3. Procedure

The subjects stood on the force platform with their feet in the required stance position. They focused on a spot on the wall at a distance of 1.5 m and stood as steadily as possible with their arms by their sides. The standardised procedure of the CTSIB over the six conditions was performed in both comfortable and tandem stance. The testing order of comfortable or tandem stance was randomised while the order of the six conditions for these stance positions was set. One 30-s trial was performed for each condition as it has been shown to be sufficient time to monitor sway but prevent exacerbation of pain from prolonged standing [24]. An inability to stand without losing balance for a 30 s time period was recorded as failure to complete the particular test.

1.4. Data analysis

Failure rates for each test condition were compared between the WAD and control subjects using a Fisher’s exact test. Both the wavelet and total sway distance analysis were performed for tests which were completed successfully. Daubechies filter 6 wavelets were used to analyse both AP and ML traces for each test condition. The first four levels of frequency captured the systematic features of the signal and higher frequency components were deemed noise.

The wavelet transform converts the signal data into coefficients which capture the information about the signal at locations within the signal for the different frequencies. The variance of the wavelet coefficients is a measure of the amount of information coming from the different locations and frequencies and is termed “energy”. By way of analogy with Ohm’s law in electricity, in this context, energy does not have units.

To examine whether there were specific features of the trace that differed between the WAD and control groups, the distribution of energies of each individual wavelet coefficient for each test was compared between groups using a Kolmogorov–Smirnov test. This showed that although differences could be found, there did not appear to be a consistent pattern of frequency, location and timing of the sway pattern for balance between tests. Rather, the differences between the sway trace of WAD and control subjects appeared to be the overall variance of the signal about zero sway (Fig. 1). In this study, we used the total of energies from AP and ML traces at the first four frequencies to summarise the information contained in the trace.

![Fig. 1. The raw signals and the smooth signal components from frequency levels 1–4 in comfortable stance depicting that the signals from the WAD subjects have more energy than control subjects.](image-url)
Total sway distance was calculated by summing the absolute sway distances from each sampling interval. For an interval \((t_i, t_j + d_i)\), the distance moved in each direction is denoted by \(d_{AP}\) and \(d_{ML}\). Then the contribution to sway distance for that interval is: \(d = (d_{AP}^2 + d_{ML}^2 + d_i^2)^{1/2}\) and the total sway distance is the sum of these.

An important difference between analyses that use (i) total sway distance [1] and (ii) wavelet energies, is that total sway distance retains signal noise and the wavelet energies exclude this component. Thus a hybrid of the distance and energy measures, smoothed distance, was calculated to provide a more direct comparison of the effects of smoothing. The smoothed distance was calculated by applying the above distance calculations to a smooth signal reconstituted from the wavelet coefficients of the first four frequencies.

The experimental data included responses from 40 subjects (20 control and 20 WAD) over 6 test conditions and for three [3] variables (distance, energy and smoothed distance) for each of these test conditions.

Exploratory analyses for all variables indicated that the standard deviation was proportional to the mean which implies that a gamma distribution could be used to model the experiment error.

The cohort by test effect was examined using a generalised estimating equation model [25] with systematic effects of cohort, test and their interactions, a Gamma distribution for the errors, a log link function and a symmetric correlation matrix for the correlations amongst the tests due to repeated measures from each subject.

By regarding the variables of distance, smoothed distance and energy as a multivariate response from each subject, the relative strengths of each in detecting cohort effects was compared using a biplot [26].

The prime focus of this paper is to provide a suitable way of quantifying sway so that it might be used to understand balance in subjects with WAD. As well, these preliminary data allow an estimation of the sensitivity of wavelet energy in identifying WAD cases.

Sensitivities of energy and total distance in discriminating control (C) and WAD cases were estimated by a Monte Carlo study. Fifteen subjects were selected at random from each group and used to calculate a quadratic discriminant function for separating control and WAD subjects on the basis of either (i) log(total energy) or (ii) total distance. The remaining five cases from each group were then classified as control or WAD using the discriminant function. This procedure was repeated 1000 times to imitate a very large sample and the frequencies of predictions accumulated in a two-way table of Observed C, Observed WAD by Predicted C, Predicted WAD. The sensitivity of the measures for detecting controls or WAD was estimated by the relative frequencies i.e. \(P(\text{Control predicted} / \text{Control observed})\) and \(P(\text{WAD predicted} / \text{WAD observed})\). The \(R^2\) statistical and graphical software was used for all calculations [27].

### 2. Results

All subjects could complete the 30-s tests in comfortable stance with the exception of one subject with WAD, for the condition of eyes closed, standing on foam. However a significant number of the subjects with WAD were unable to complete the 30-s tandem stance tests. Subjects with WAD lost stability more often than control subjects, except in the conditions of standing on foam with eyes closed and with the visual dome, which were equally difficult for both the control and WAD groups. The number of subjects who were unable to complete the 30-s tandem stance test for the WAD and control groups and the probability of difference of failure rates between groups for each test is depicted in Table 1. As a result, signal analysis was not performed on tandem stance tests.

The predicted cohort-test means and their 95% confidence intervals on the log scale for each measurement variable for comfortable stance tests are shown in Fig. 2. In all but the test of eyes open firm surface, there is a clear difference between the control and WAD cohort means of

### Table 1

The number of control and whiplash subjects unable to complete tandem stance tests and the statistical significance of group difference in failure rates

<table>
<thead>
<tr>
<th>Test</th>
<th>Controls</th>
<th>Whiplash</th>
<th>P (not different)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes open firm</td>
<td>0</td>
<td>4</td>
<td>0.11</td>
</tr>
<tr>
<td>Eyes closed firm</td>
<td>4</td>
<td>16</td>
<td>0.00</td>
</tr>
<tr>
<td>Visual conflict firm</td>
<td>4</td>
<td>13</td>
<td>0.01</td>
</tr>
<tr>
<td>Eyes open soft</td>
<td>0</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>Eyes closed soft</td>
<td>17</td>
<td>18</td>
<td>1.00</td>
</tr>
<tr>
<td>Visual conflict soft</td>
<td>15</td>
<td>18</td>
<td>0.41</td>
</tr>
</tbody>
</table>

### Table 2

Test sensitivities for both total energy and total distance for detecting controls or subjects with WAD for each of the six comfortable stance tests

<table>
<thead>
<tr>
<th>Test</th>
<th>(P(\text{C predicted} / \text{C observed})) Total energy</th>
<th>Total distance</th>
<th>(P(\text{WAD predicted} / \text{WAD observed})) Total energy</th>
<th>Total distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes open firm</td>
<td>0.83</td>
<td>0.85</td>
<td>0.48</td>
<td>0.21</td>
</tr>
<tr>
<td>Eyes closed firm</td>
<td>0.81</td>
<td>0.87</td>
<td>0.74</td>
<td>0.19</td>
</tr>
<tr>
<td>Visual conflict firm</td>
<td>0.74</td>
<td>0.67</td>
<td>0.64</td>
<td>0.24</td>
</tr>
<tr>
<td>Eyes open soft</td>
<td>0.89</td>
<td>0.91</td>
<td>0.48</td>
<td>0.20</td>
</tr>
<tr>
<td>Eyes closed soft</td>
<td>0.88</td>
<td>0.98</td>
<td>0.63</td>
<td>0.34</td>
</tr>
<tr>
<td>Visual conflict soft</td>
<td>0.88</td>
<td>0.88</td>
<td>0.59</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Fig. 2. Comparison of cohort differences for the Distance, Energy and Smoothed Distance measures of traces from the six comfortable stance tests. The means and 95% confidence intervals for the control cohort are plotted as (○) and for the WAD cohort as [+].

Fig. 3. Biplot showing the relationship amongst measurements and the discrimination amongst subjects for each measure.

Fig. 4. Comparison of a control (left side) and a WAD (right side) sway pattern that have similar distance measures. The ML and AP traces are plotted in the two top rows, the accumulated distance and smoothed distance are plotted in the third row with the total distances shown by dashed lines. The accumulated energy is plotted in the fourth row.
energy and smoothed distance. The unsmoothed distance measure did not detect any differences across the six test conditions.

Table 2 lists the sensitivities of both total energy and total distance for detecting controls or subjects with WAD for each of the six comfortable stance tests.

To further explore how the different results between methods of analysis arise, we compared measurements from the visual conflict—soft surface test. The biplot in Fig. 3 has the scores of the first two principal components for each subject, labelled as “n” (control subjects) or “w” (whiplash subjects), and the vectors that show subject differences for each measure and the correlation of these measures. The rankings of subjects by energy and smoothed distance are similar but quite different to the rankings along the distance measure did not detect any differences across the six test conditions. In contrast, no differences between WAD and control subjects could be demonstrated when total sway distance was analysed. This finding, as well as the non-significant correlation between energy and total sway distance for the majority of test conditions and the fact that total distance had very poor sensitivity in detecting subjects with WAD (Table 2), implies that the information gained from the total sway distance is not sufficient to demonstrate altered balance responses in subjects with WAD.

The results of the study suggest this disparity between the analyses can be explained by considering the smoothing nature of wavelet analysis. The raw data from a sway trace is a combination of the amount of sway (a systematic effect) and sampling error. The sway is the required response from the samples are taken so frequently that they have the same sampling interval. Assume that the trace is continuous or that the samples are taken using the data from the six comfortable stance conditions as all subjects, except one whiplash subject, successfully completed each condition. Wavelet analysis demonstrated a significant difference between the WAD and control subjects for all test conditions except standing on a firm surface, eyes open. Wavelet analysis also demonstrated moderate sensitivity particularly in tests of altered vision, in discriminating between control and subjects with WAD. In contrast, no differences between WAD and control subjects could be demonstrated when total sway distance was analysed. This finding, as well as the non-significant correlation between energy and total sway distance for the majority of test conditions and the fact that total distance had very poor sensitivity in detecting subjects with WAD (Table 2), implies that the information gained from the total sway distance is not sufficient to demonstrate altered balance responses in subjects with WAD.

The results of the study confirm that deficits in postural responses can be demonstrated in those subjects with chronic WAD who complain of dizziness and or unsteadiness compared to healthy control subjects. Importantly, the results demonstrated that the tests selected and methods of analysis are important factors to consider to detect altered balance responses in subjects with WAD complaining of dizziness and or unsteadiness from both a research and clinical perspective.

With respect to the tests selected, control subjects could maintain steadiness for 30 s in tandem stance tests on a firm surface while subjects with WAD frequently lost their balance. Tandem stance on foam conditions however, was equally difficult for both WAD and control subjects, a feature found previously for healthy subjects [28] confirming that it is not a suitable test to use when investigating balance problems. Thus the ability to complete 30 s of tandem stance tasks on a firm surface (eyes open/eyes closed), may be a suitable clinical test to identify potential balance problems in subjects with WAD however further research into the aetiology of these disturbances will be necessary. From a research perspective the use of comfortable stance is suitable provided the appropriate signal analysis is used, as significant differences were seen between groups for most comfortable stance tests. However some comfortable stance tests appear to be more sensitive than others. Test with altered vision appear to be more sensitive than tests with vision (Table 2).

3. Discussion

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The results of the study suggest this disparity between the analyses can be explained by considering the smoothing nature of wavelet analysis. The raw data from a sway trace is a combination of the amount of sway (a systematic effect) and sampling error. The sway is the required response from each experimental condition so any summary should exclude the random sampling error. Both the wavelet analysis (deriving the energy) and smoothed distance measures do this while the distance of the raw trace does not. This means that the total distance of sway is not as precise a measure of balance and less able to detect differences between groups.

The following illustration helps to explain this outcome. Envisage part of a trace where the local mean is approximately constant but that the samples indicate high frequency vibrations about the mean. The mean in this case is indicative of no sway but distance is ‘accumulating’ due to the summing of many random fluctuations.

A more formal mathematical explanation uses the derivation of trace length by integrating the distances of each sampling interval. Assume that the trace is continuous or that the samples are taken so frequently that they have the same properties as a continuous trace. Denote the trace as a function of time $t$ by $y = f(t)$. The length of the trace in a small instant of time is $dL = (dy^2 + dr^2)^{1/2}$. Writing $dy = f'(t)dt$, collecting terms and integrating gives $L = \int (1 + f'(t)^2)^{1/2} \, dt$ and we observe the contribution of the squared derivative in determining signal length. For highly fractal signals, the magnitude of the derivative at each sampling point is
ongoing problems of chronic WAD or symptom amplification due to side effects of medications, anxiety caused by either the ongoing problems of chronic WAD or symptom amplification due to the litigious nature of WAD [20, 30–32]. Other researchers assert that trauma in a whiplash injury may damage or functionally impair any of the key systems for postural control [1, 33, 34]. The results of this pilot trial will provide important directions for future studies designed to investigate the possible aetiology of such balance disturbances in WAD.

4. Conclusion

This study has determined that balance is disturbed in whiplash subjects who complain of dizziness and or unsteadiness in both comfortable and tandem stance and that timed standing tests in tandem positions could potentially be used by clinicians to identify balance problems after WAD. The capacity for the comfortable and tandem tests to differentiate WAD clients with and without balance problems and the possible aetiology of these disturbances requires further investigation. This study also determined that the method of analysis of the sway pattern can influence the results and interpretations from a study. Wavelet analysis was found to differentiate between groups of subjects with WAD and healthy controls in most test conditions carried out in comfortable stance and had moderate sensitivity in detecting subjects with WAD. It is recommended that future studies measuring sway trace should consider the benefits of using wavelet analysis as a form of data analysis.

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References