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SeeSway – a free web-based system for analysing and exploring standing balance data

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Highlights

- SeeSway is a free website for analysing instrumented balance tests
- Filtering: Wavelet, Butterworth and averaging filters
- Standard Analysis: Techniques such as path length and range
- Other analysis: Entropy, detrended fluctuation and wavelet
- The program focuses on simple yet powerful data analysis

Title: SeeSway – a free web-based system for analysing and exploring standing balance data

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Abstract

Background and Objectives: Computerised posturography can be used to assess standing balance, and can predict poor functional outcomes in many clinical populations. A limitation of this technique is the disparate signal filtering and analysis techniques, with many methods requiring custom computer programs. This paper discusses the creation of a web-based software program, SeeSway (www.rehabtools.org/seesway), which was designed to provide powerful tools for pre-processing, analysing and visualising standing balance data in an easy to use and platform independent website.

Methods: SeeSway links an interactive web platform with file upload capability to software systems including LabVIEW, Matlab, Python and R to perform the data filtering, analysis and visualisation of standing balance data. Input data can consist of any signal that comprises an anterior-posterior and medial-lateral coordinate trace such as center of pressure or mass displacement. This allows it to be used with systems including criterion reference commercial force platforms and three dimensional motion analysis, smartphones, accelerometers and low-cost technology such as Nintendo Wii Balance Board and Microsoft Kinect. Filtering options include Butterworth, weighted and unweighted moving average, and discrete wavelet transforms. Analysis methods include standard techniques such as path length, amplitude, and root mean square in addition to less common but potentially promising methods such as sample entropy, detrended fluctuation analysis and multiresolution wavelet analysis. These data are visualised using scalograms, which chart the change in frequency content over time, scatterplots and standard line charts. This provides the user with a detailed understanding of their results, and how their different pre-processing and analysis method selections affect their findings.

Results: An example of the data analysis techniques is provided in the paper, with graphical representation of how advanced analysis methods can better discriminate between someone with neurological impairment and a healthy control.

Conclusions: The goal of SeeSway is to provide a simple yet powerful educational and research tool to explore how standing balance is affected in aging and clinical populations.

Keywords: posturography; balance; force platform; center of pressure; falls

Introduction

Computerised posturography can be used to assess aspects of standing balance that are not possible from clinical tests such as timed standing or subjective rating scales (e.g. Berg Balance Scale). A common method of assessment is to perform a static standing trial during which a person's postural sway is collected using outcome measures such as center of pressure (COP) or center of mass displacement [1]. These assessments can provide an insight into how much a person sways when they are attempting to stand naturally. Excessive sway, or the opposite presentation of excessive rigidity, may indicate an impaired neural control strategy and could be an early predictor of poor long term outcomes such as falls [2]. Balance impairments are also prevalent in many clinical populations, including hearing loss [3], idiopathic neck pain [4], post-surgery [5], cancer [6], joint injury [7], and chronic obstructive pulmonary disease [8].

Prior to the current decade the implementation of posturography was very limited, as it required expensive systems such as commercial force platforms or inertial monitoring units [9]. However, an influx of low-cost, widely accessible technology that either includes or provides an alternative to these sensors has become available. For example, studies have shown that systems including the Nintendo Wii Balance Board [10-12], Microsoft Kinect [13, 14], and smartphones [15] provide valid data for quantifying postural sway. Importantly, the creation of these systems has allowed for their use in assessing clinical populations, with a number of studies showing their ability to discriminate between healthy and clinical populations [16-18], identify longitudinal changes in function [19-21] and predict poor outcomes [22-24].

A major limitation of computerised posturography is that the data acquisition and processing techniques used can have a very large impact on the results of some outcome measures, and this makes comparison and compilation of data across studies fraught with error [25]. While it is difficult to standardise data acquisition hardware across research centers, it may be possible to provide a standardized analysis framework for posturography related data analysis to ensure consistency across studies. An issue with this is that it is still unknown what the optimal signal preparation and analysis methods are for specific populations and assessments. There are a wide variety of filtering techniques, including traditional finite impulse response (for example the Butterworth filter) and wavelet filter banks. Furthermore, the optimal filtering thresholds can vary between assessment tasks, with single leg standing requiring a higher lowpass frequency threshold than double leg standing. Additionally, analysis methods range from the simple (for example – calculating the maximum range the COP moved during a trial) through to the complex (for example – detrended fluctuation analysis). The lack of definitive guidelines is partly due to the limited research in the area, and the difficulty in comparing filtering methods and outcome measures due to the need to create custom software to perform these analyses.

In an effort to overcome these issues, we have created an online, platform independent interactive webpage that allows the user to easily examine their data using different filtering and analysis techniques. This paper describes the creation of a freely available, internet-based software package (SeeSway, available at http://www.rehabtools.org/seesway.html) for pre-processing and analysing posturography data that is compatible with any device that exports raw postural sway related data.

Design Considerations

The online analysis program interacts with the user in the same manner as a standard dynamic website. SeeSway is built using a combination of standard website programming languages including HTML, Javascript, PHP and CSS. The novelty of this system is that the website is linked to server-hosted LabVIEW, Matlab and C# executables and dynamic link libraries via a Websockets protocol, with the capacity to access other programming languages such as Python and R via a backend command line interface hosted on the local server. This allows for simplified access to the user input data, distribution and processing of the data on computers linked to the server computer (at the time of writing: Windows 8 Professional Core-i7 with 16Gb RAM and 500GB solid state hard drive), and reporting back to the user. This flexible combination of software systems has the potential to allow for interaction with code created in all major programming languages, and any server-hostable visualisation software that produces HTML output such as Highcharts and Plotly.

A variety of methods were explored to link the user interface webpage with the analysis programs. A decision was made to integrate Websockets due to its cross-platform compatibility and its ease of data transfer with the server hosted Ubuntu virtual machine. Data transfer was achieved using Labsockets (Bergman Mechatronics, USA), which is a software program designed to replicate a LabVIEW graphical user interface in a PHP format. This portal allows for LabVIEW programs to be run natively, but also allows for interfacing with other programming languages and compiled executables via methods such as .NET and ActiveX calls or using the inbuilt functions such as the Matlab Script node. Importantly, the individual programs which are represented as websites can be run on remote computers yet still hosted on the server. As an example, during debugging the SeeSway program was being tested on a computer in Singapore which sent the webpage to the server in Australia where it was hosted. This results in the ability to minimise the computing requirements of the server by simply adding more computers to run any additional programs, with the server only hosting the resulting webpages.

Description of Method/System

SeeSway provides a suite of signal pre-processing, analysis and visualisation methods that can help the user optimise the quality of their data and explore analysis techniques that could provide insight into the standing balance of their participants. These include:

<u>Pre-processing Filtering Protocols</u>

1. Lowpass Butterworth filter. This includes a selectable filter cut-off threshold (defaults to 10hz) and order (defaults to 6th order). The Butterworth filter is implemented using a reflection padding method, which creates reversed copies of the dataset and appends these to the start and end of the original dataset, performs the filtering, then removes these padded segments before further analysis [26].
2. Non-weighted and weighted moving average filters. The non-weighted moving average filter is a simple mean filter (default 5 samples length), and while these are not commonly used for analysis they are very effective at removing transient noise from a signal at the expense of frequency domain signal integrity. The weighted moving average method is a Henderson 13-term moving average filter [27].

3. Wavelet-transform based filtering. Discrete wavelet transform filters have numerous potential benefits in terms of processing discrete, non-linear signals. Their drawbacks include a lack of precision with respect to filter cut-off thresholds due to their usage of cascading filter banks. Therefore three iterations are provided in the analysis program, with lowpass cut-offs of 12.5Hz, 6.25Hz and 3.125Hz available. The Coiflet-5 wavelet was chosen as the mother wavelet as it was deemed to most closely match the shape of the COP signal, however it provides almost identical results to other wavelets such as higher order Symlet and Daubechies wavelets for posturography analysis [28]. The website defaults to the Coiflet-5 wavelet filter.

The effect these filters have on the data are displayed graphically, and in the time-frequency domain using scalograms derived from a Complex Morlet continuous wavelet transform. This allows the user to examine their data to determine the optimal filtering method for their specific tasks.

<u>Data Analysis</u>

The current iteration of the website takes three one-dimensional arrays from a single spreadsheet file, in each of the first three columns. The first array consists of the medial-lateral data, the second array the anterior-posterior data and the third array corresponds to vertical force. As per standard posturography analysis, the first two arrays are analysed independently to calculate axis specific results. These two arrays are also combined using basic Pythagoras theory to determine a combined axis displacement for each sample point, from which total scores are derived. The third axis is only used to obtain body mass and vertical force fluctuation measures. To aid in conversion of the end-users data to this format, we have provided a detailed how-to video (available at http://www.rehabtools.org/balance-

analysis-notes.html) which shows the creation of a simple macro in Microsoft Excel that converts data from a commercial force platform into the correct format for the website.
A detailed description of each of the outcome measures reported on the website is not provided in this article for many reasons. As the website evolves and knowledge about the important outcome measures to derive from posturography increases, more variables will be added and some of the currently included ones may be removed or modified. Additionally, this paper focuses on the technical aspects and goals of the website, and to discuss the specific details of each outcome measure is beyond its scope. For readers interested in the different outcome measures we refer you to the citations for each of the outcome measures described below, or to the SeeSway site where additional information is provided.

Common outcome measures with reported reliability and sensitivity to change including path length, velocity, amplitude, root mean square and standard deviation are reported [21, 29]. Additional outcome measures that have promise based on previous research, but are less well established and not typically included in standard posturography analysis software, including wavelet-based signal decomposition [21, 30, 31], sample entropy [28, 32, 33] and detrended fluctuation analysis [21, 34] are also reported. This is an important aspect of the site, as some of these variables may with further research prove to be important, but are currently rarely implemented due to the difficulty of analysis (for example, the requirement for custom computer coding). As an example, Figure 1 shows a wavelet transform scalogram of the medial-lateral COP trace for A) someone with advanced Parkinson's disease, and B) a healthy control subject. We feel that the graphical visualisation of these data in an easy to interpret format can assist the user to make an informed decision about the importance of the variables obtained.

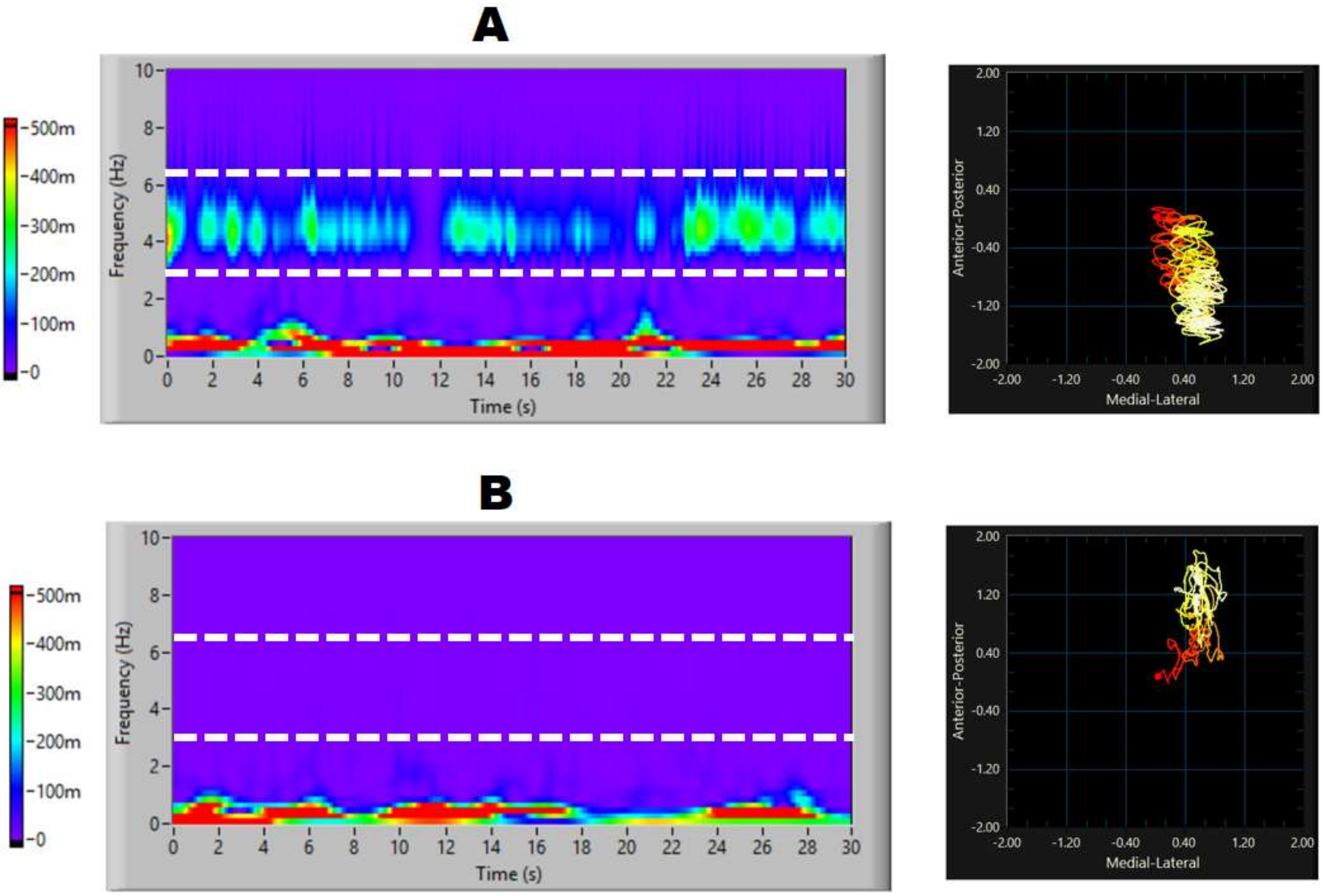

Figure 1. An example of the data visualization available in the online program. A wavelet scalogram for the medial-lateral balance trace of A) a person with advanced Parkinson's disease, and B) a healthy control subject is shown on the left of the image. Note the similarity in the intensity of the signal at low frequencies (below 1.5Hz), but the distinct difference in the 3.125Hz to 6.25Hz bandwidth. This visually displays the postural sway associated with tremor in this person. The black XY graphs on the right display the traditional postural sway "spaghetti graph". This example is using center of pressure data from a force platform, and reflects the persons sway during a 30 second trial. Note that the amplitudes on each axis (ie. the maximum displacement) are similar between people, and therefore only additional analysis methods would discriminate between the two people.

The online pre-processing and analysis software defaults to the recommended settings, and allows the user to easily modify them to the input settings that they prefer. This allows the user to inspect their data and examine how different settings change the results of their analyses. This is particularly important for the detrended fluctuation analysis and sample entropy variables, as modifying these settings will produce notable effects on the results. It is then up to the end-user to make decisions based on prior research and the results provided by the website as to which settings are optimal for analysing their data.

At the time of writing of this article, all pre-processing and analysis except sample entropy is implemented using the LabVIEW Advanced Signal Processing Toolkit algorithms. These methods are described in detail in the publication "Signal Processing Toolset User Manual" available at ni.com (http://www.ni.com/pdf/manuals/322142b.pdf). Where applicable these have been tested against Matlab algorithms and provide identical results. Sample entropy is calculated using Matlab and the often cited algorithm provided at physionet.org [35].

Discussion

In this section we describe key aspects of the website, including important questions raised during the development process and planned changes in the near and long-term.

Mode of Availability of the Software

A key factor in the decision to have a strong component of online data analysis versus locally installed software is to allow it to be device and operating system independent. One of the key questions in the design stage of this site was to make it truly open source in a way similar to software such as ImageJ [36] or EEGLAB [37]. This would be possible by integrating user changes to background code in close to real-time, but we deemed that this posed too many potential problems with respect to website maintenance, data privacy and costs. Although we believe that this would provide numerous advantages, it would also shift the focus more towards highly experienced programmers who are not the target audience of this project.

A significant challenge for this site is that the long-term viability of a free model is always in question. However, in many ways the free model suits a website of this style, as it allows for software such as LabVIEW, Matlab and graphing packages such as Plotly and Highcharts to be used without the host requiring a paying subscription. Consequently, the major ongoing costs of this website relate to expansion and content creation. Key-person risk is also a factor, as the first author operates the site, performs the coding and maintains the server. However, this can be transferred if it is required in the future. In a worst-case scenario it is also possible to convert from an online analysis method to a locally-installed system whereby the end user downloads the analysis programs and runs it on their own computer. However, this removes the core aspect of operating system independency that is a key factor in the creation of this site.

Choice of Variables Reported

One of the hardest decisions to make has been which outcome measures to include on the website. We have included many analysis methods, ranging from simple amplitude measures through to split regression detrended fluctuation analysis and sample entropy. The methods chosen were because either we ourselves or other researchers have reported their utility to a point where we felt they may be beneficial. We have also tried to include measures which we feel have the potential to be used in clinical settings. Our team has a core interest of in-clinic assessments performed by clinicians with patients. This has provided us with an insight into which outcome measures have the potential for translation to routine screening, and has emphasised the importance of identifying outcome measures that are modifiable. This refers to the ability to explain what the outcome measures means to a “posturography layman” – i.e. a typical patient, and to implement a rehabilitation strategy to improve future results. Variables such as sample entropy and detrended fluctuation analysis do possess face validity with respect to standing balance assessment, in that they quantify regularity and complexity of the movement of the center of mass respectively [32]. A more regular and less complex movement may be a good sign, for example there is less uncontrolled and erratic sway in someone with ataxia, or a bad sign, for example that to maintain standing balance requires more cognitive resources and natural sway is inhibited [38]. The biggest problem with these variables is explaining them in a clinical context to either clinicians or patients. Conceptually they are more difficult to explain than standard measures such as path length (example explanation – this measure tells us the total distance you swayed during the test, with higher scores meaning your body moved more) or even the wavelet based analyses (example explanation – the moderate frequency measure tells us how much "quick" movement your body does during standing, with higher values meaning your body performs a lot of rapid movements). This does not discount their potential use as a research and diagnostic tool though, and therefore they and other techniques should be further studied.

Importantly, the outcome measures implemented are not by any means exhaustive, and will evolve as the site is expanded and new tools are identified. We hope that as the site gets more usage it will eventually provide a comprehensive range of outcome measures that we and others contribute to. As a first step, we feel that the measures provided in the current iteration provide a reasonably well-rounded array of temporal, spatial, frequency and chaos outcome variables.

Status Report

At the time of writing the SeeSway website was fully operational, with latency times that were deemed acceptable by the end-users who trialled the software.

Lessons Learned

Technology and software is not future proof. Potentially the most difficult aspect of the online analysis programs was creating a simple system for non-programmers with limited technical expertise that provided a layer of uploaded data security and anonymity. During the creation of this site, a file sharing system that was very effective (Dropittome) was incorporated and systems built around using it to transfer data, but it was shut down in June 2017. This reinforced the need to have multiple options and redundancy for every aspect of the project, and to attempt to forecast the longevity of the tools implemented on the site. For this reason we have utilised automated Dropbox file synchronisation as the first stage of data transfer instead of a custom website based FTP (file transfer protocol) method. Dropbox provides its own security protocols, including file splitting encryption, and is one of the most widely used and recognised file sharing programs available. Once the data are synchronised on the host computer a suite of further measures are used to check for data integrity, maintain anonymity and destroy inappropriate files. Additionally, for an extra layer of protection a program that can be installed on the user's computer is available to download from the website (http://www.rehabtools.org/encode.html) which allows the user to batch convert the names of every file they intend to analyse prior to uploading. This program randomises and modifies the characters in the file names, and stores the key only on the user's computer. After the data are analysed, the file names can be reconstructed simply using the stored key. This allows for true anonymity of the data files regardless of any issues with the online server system.

Future Plans

SeeSway is a freely available, evolving platform for posturography assessment, with the planned addition of new outcome measures by both the development team and hopefully other research groups. The nature of the website means it is possible to easily integrate methods written in a variety of programming languages. It is therefore hoped that the posturography community will contribute either raw code or executable files for additional outcome measures of interest.

One area of the site that we would like to significantly improve is the data visualisation. With dashboard software such as Tableau and interactive Javascript graphing packages becoming more widely recognised, interactive data presentation will soon become the norm. We have already experimented with using Highcharts and Plotly HTML files embedded into the webpage, and found it to be particularly informative with respect to examining the wavelet-based analyses. We therefore expect to integrate these or similar methods in upcoming evolutions of the website.

If the SeeSway platform proves to be of benefit to the community and is used regularly, there is the opportunity to host servers in different locations throughout the world to improve responsiveness. This process is very simple and can be performed on the majority of Windows computers with access to the internet and open communication ports. It can also be hosted using dedicated cloud computers, such as those offered by Amazon Elastic Cloud Compute. Both options will be explored to determine the optimal compromise between cost savings (local hosting) and server responsiveness and guaranteed uptime (cloud hosting).

A longer-range goal is also to allow data sharing and potentially “big data” analysis. This would consist of a minimal database setup in which the end-user uploads their data files, along with basic demographic and descriptive data specific to the clinical population, and can analyse their data both independently and in comparison with other data from healthy and clinical cohorts. At present we are hesitant to implement a database as we appreciate the ethical and data privacy issues that this would present, however it is something that will be considered in the future if there is demand for it.

In conclusion, SeeSway is an attempt to create a freely available yet powerful standing balance analysis website. We believe that it has great potential as both an educational and research tool in the field of computerised posturography.

Conflict of Interest: There is no direct financial conflict of interest at present, nor any plans for there to be one in the foreseeable future. Author RAC operates and maintains the site referred to in this paper. Author RAC is supported by a National Health and Medical Research Council R.D. Wright Biomedical Fellowship (#1090415).

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