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ABSTRACT

Falls are a prevalent problem among elderly populations. Falls increase the cost of healthcare, frequently cause severe injuries, and negatively affect quality of life. Lack of postural stability is a major contributing factor to falls, with postural stability defined as the correct biomechanical execution based on sensory feedback. Types of sensory feedback include vision, vestibular, proprioceptive, and somatosensory. This study focuses on the lack of postural stability in quiet standing (standing upright and still) due to somatosensory and vision deficiencies. To track these deficiencies, fifty-one subjects stood for sixty seconds on two force plates, and their center of pressure (COP) time series were extracted. All subjects completed three trials with eyes closed or open while standing on five foam thicknesses that simulated various levels of somatosensory deficiencies at the feet, a common symptom in people with a high risk of falling (e.g., diabetic populations). To quantify these somatosensory deficiencies, Detrended Fluctuation Analysis (DFA) was performed on all COP time series. It is hypothesized that DFA on COP time series can track deficiencies in the somatosensory and vision feedbacks. Though this study does not cover actual somatosensory deficiencies, it could offer a validated measure to future studies comprised of participants who suffer from peripheral neuropathy (e.g., diabetic populations).

REVIEW OF LITERATURE

Falls are prevalent amongst the elderly population, particularly in the United States due to the Baby Boomer generation's current age. These falls result in a high cost for the United States government in Medicare expenditures for fall treatment. One-third of adults over the age of sixty-five are expected to fall at least once per year. On top of this, the Baby Boomer population will soon result in an even higher population of elderly persons. With these considerations, the U.S. Department of Housing and Urban Development estimated in 2017 that the cost of falls in 2020 would be $59.7 billion and would only increase as time progresses [1]. Research to prevent falls will thus not only help improve the quality of life for aging citizens but has the potential to greatly decrease health costs.

Falls are caused by deficiencies or faults within the body's feedback system or central nervous system. The body's sensory feedback is comprised of four different systems: the visual, proprioceptive, vestibular, and somatosensory systems. The visual system is perceived with the eyes. The proprioceptive system is perceived through receptors on the skin, joints, and muscles. The vestibular system is perceived through the cochlea in the ear. Finally, the somatosensory system is perceived by the skin or internal organs. These systems work together to achieve desired biomechanical tasks, such as standing in place. However, it has been shown that as one feedback system is removed the others perform at a higher level to compensate [2]. For example, if the visual and somatosensory feedback systems are removed or damaged, the proprioceptive and vestibular feedback systems will perform at a higher level.

To study the somatosensory feedback in human balance, Center of Pressure (COP) or Center of Mass (COM) is extracted while subjects stand on a force plate. COP indicates the position of the vertical force projected onto a two-dimensional axis. COM is different than COP because it considers the entire body. While COP is two-dimensional, COM is three-dimensional, as the COM of the body is above the feet (somewhere in the positive z direction). See Figure 1 for a visual comparison of COP and COM. The COP can be separated into the anteroposterior (AP) and mediolateral directions (ML). Relative to a person's body, the AP direction is in front of and behind, while the ML direction is from side to side.

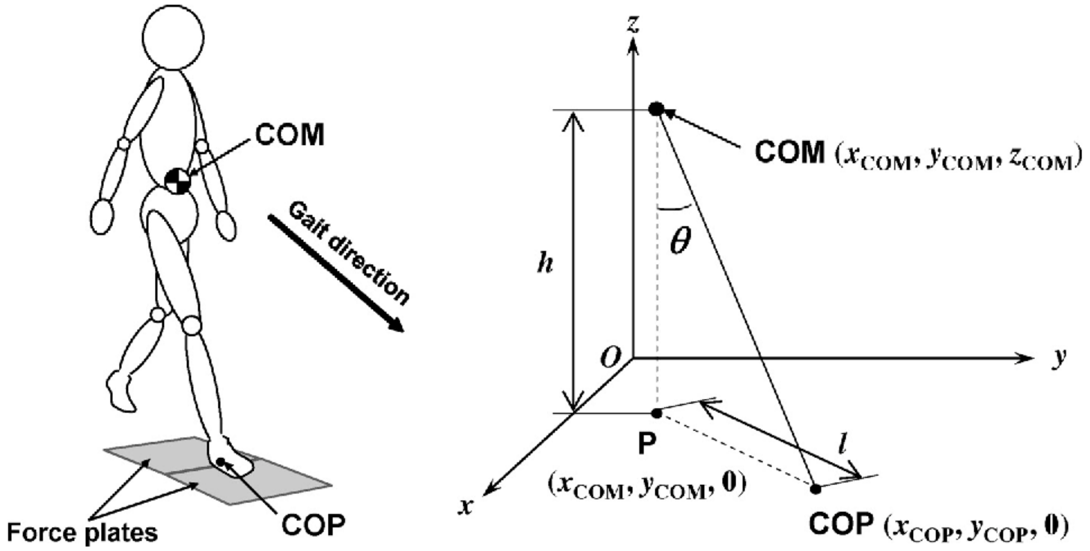

Figure 1: COP Compared to COM [3]

Testing is performed with the somatosensory feedback altered or unaltered. Force plate ground reaction forces and moments are used to calculate COP [4]–[6] or COM [2], [4] data. To simulate a deficiency in the somatosensory feedback experienced by a fall-prone elderly person or someone suffering from diabetes, studies either freeze the feet to numb them [7] or use foam between the feet and force plate [2], [7]–[11]. Foam has been proven to be more effective when simulating somatosensory deficiencies compared to freezing feet [7].

The COP changes over time and cannot be defined as a function; therefore, it is considered a time series. Once the COP time series is extracted, it must be analyzed by extracting metrics that can translate to a medical meaning. Some meaningful metrics in human balance are entropy [11], fractal analysis [5], [12], [13], and detrended fluctuation analysis (DFA) [14]. This line of research suggests using non-linear measures to analyze COP is effective. However, there seems to be a lack of research using DFA as the metric to study the COP time series.

DFA defines the complexity of a time series by classifying the signal as white, pink, or brown noise [14]. In short, DFA linearizes partitions of a time series, and the root mean square (RMS) fluctuation is taken from this linearization. This is repeated for various partitions, and the partitions are combined back together in a log-log graph (RMS fluctuation vs. partition width). The slope of the log-log graph is α, the main extracted value from DFA. An α value of 0.5 is white noise, a value of 1 is pink noise, and a value of 1.5 is brown noise. The results and some steps of a DFA analysis are shown below.

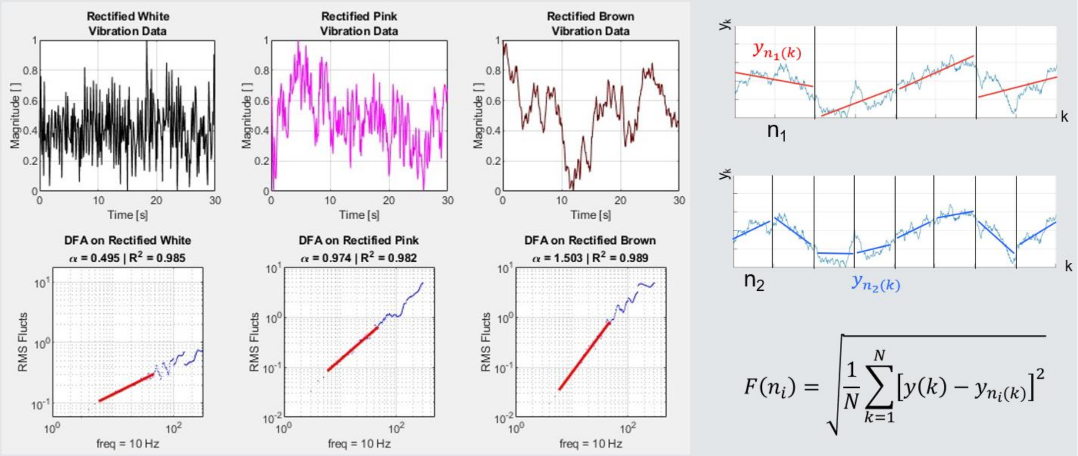

Figure 2: Visualization of DFA

Various studies on biological systems within humans have determined that pink noise is found in healthy systems. For example, pink noise has been proven to help people fall asleep [15]. Most importantly, dynamics similar to pink noise demonstrate healthy characteristics of human walking [16]. This information suggests that during quiet standing, healthy subjects should show a pink noise pattern. As the foam thickness is increased, simulating a greater deficiency in the somatosensory feedback, the DFA is expected to deviate from an α value of 1 (pink noise) to a different value (white or brown noise). If there is a deviation between healthy subjects' α values and subjects that are "diseased" (standing on foam) then there is potential for early tracking of somatosensory deficiencies through DFA on COP time series. This could also have the potential to diagnose postural deficiencies in diabetes earlier because a decrease in somatosensory feedback at the feet is common to those with the disease. Using DFA on the COP time-series could show potential to diagnose somatosensory deficiencies. If the α value varies significantly as the foam thickness is increased, it can be assumed that the α value would also change the greater the somatosensory deficiency is in a patient.

METHODS

The data analyzed in this study was obtained at the University of Kansas [11]. Fifty-two young and healthy participants stood on five levels of foam (0", ⅛", ¼", ½", and 1") while their COP time series was recorded in both the AP and ML directions. Participants' visual condition was also varied (eyes open (EO) or eyes closed (EC)). Three 60-second trials were completed for every foam thickness and each visual condition, resulting in thirty trials per subject. Ground reaction forces were collected by an AMTI force plate, and data was sampled at 100 Hz through a Cambridge Electronic Design MkII data acquisition system [11].

Data analysis was completed entirely in MATLAB. All raw data for each subject was graphed so it could be visually checked for errors. An example of the raw data is shown in Figure 3. Upon viewing the data, it was observed that subject 22 showed a large deviation from other subjects. To help create a stronger correlation with the data analysis, this subject's data was excluded. The data was then filtered and downsampled. The filtering technique was a low pass filter of 10 Hz, and the data was downsampled to 50 Hz (Figure 4).

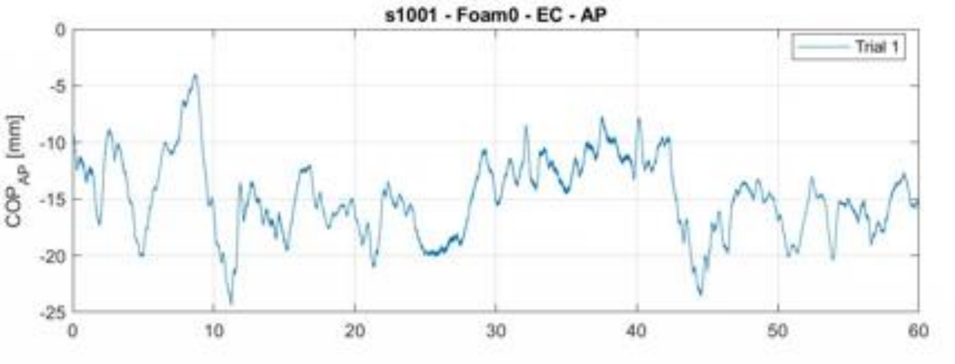

Figure 3: Raw COP data

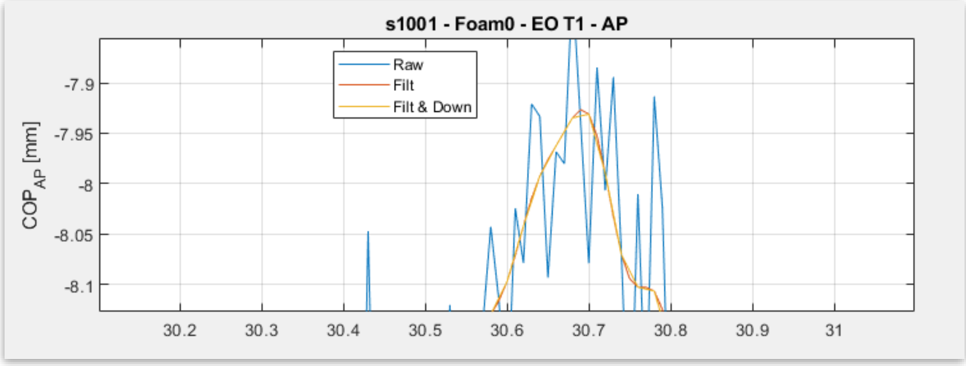

Figure 4: Filtered and downsampled data

Figure 3 shows the raw data from a trial. The specifics of the trial are also shown in the figure: "s1001" denotes subject 1, "Foam0" denotes the no foam control, "EC" denotes the EC condition, and "AP" denotes the AP direction. Figure 4 is similarly labeled; however, it contains three different lines labeled in the legend. The light grey line represents the data used for DFA.

DFA was then performed with a minimum partition time of 0.1 seconds and maximum partition time of 15 seconds on the filtered and downsampled data, and the DFA alpha and R-Squared values were extracted for each trial. The mean α across trials and subjects was taken for each set of conditions (visual condition and foam level). Finally, percent change within each subject with respect to no foam was utilized to visualize the impact of the somatosensory deficiency.

RESULTS

The results of the study are shown in the graphs in Figure 5. The lines represent the mean of all subjects' data. The graphs show the different foam thicknesses and their percent change from the no foam control (F_0). The R-Squared value is displayed in the titles of each plot to show the reliability of the α values. The dashed line represents the standard deviation of the α values.

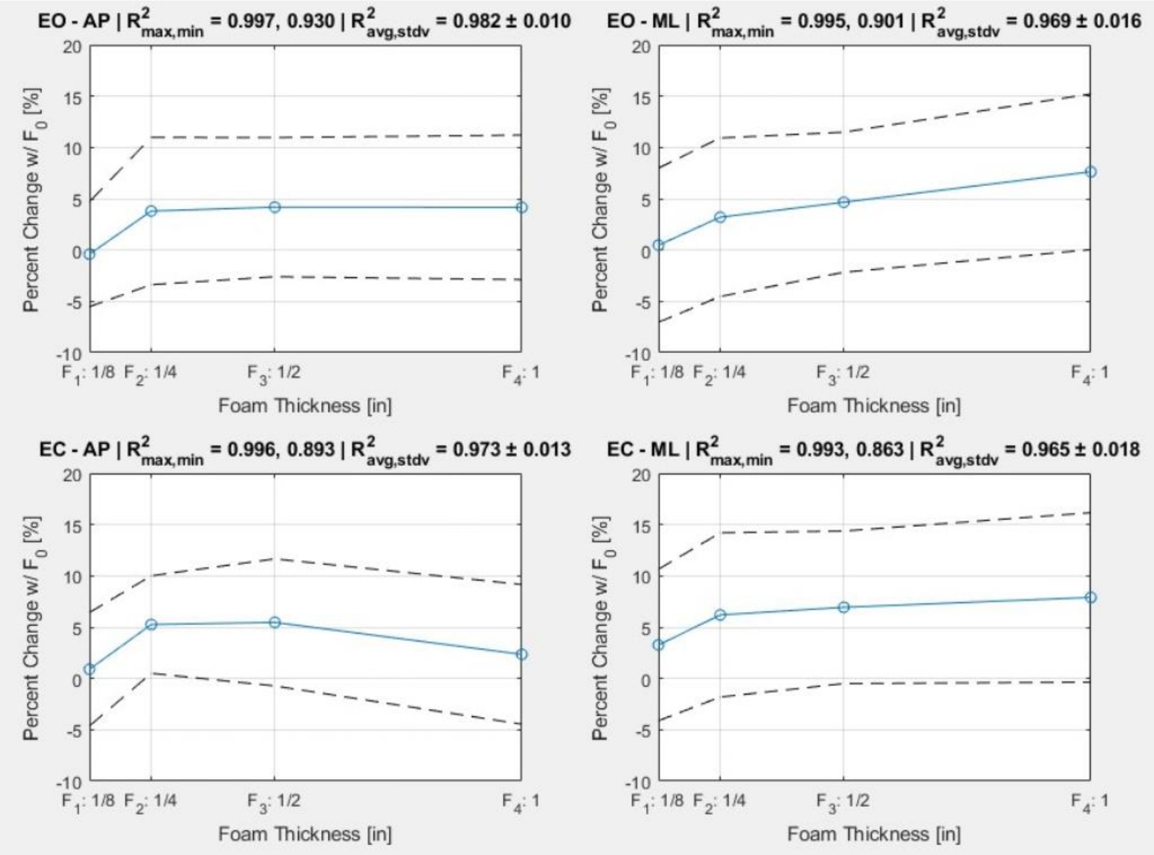

Figure 5: DFA α percent change from control

In all four conditions, there was a noticeable increase in percent change between the ⅛" and ¼" foam. The change was around 4% for each condition at this point. Along with this, all conditions besides EC in the ML direction had a nearly 0% change between no foam and ⅛" foam. The EO, AP direction had a difference between the no foam control and the ⅛" foam that was nearly 0%. This condition had the initial jump seen in the other conditions, but then it plateaued and showed almost no additional changes between foam thicknesses ¼" and 1". The EO, ML condition also had nearly no change from the no foam control to the ⅛" foam. It also had the initial jump but then continued to show increases in percent change from no foam to the 1" foam. For the EC, ML foam condition the percent change from no foam to 1" about 8%. Again, the EC, AP condition remained near 0% change between the no foam control and the ⅛" foam. It also had the jump between ⅛" and ¼" foam. However, this condition resulted in a decrease in the percent change between ½" and 1" foam. This unique result will be discussed later. Lastly, the EO, ML condition did have a substantial change between the no foam control and the ⅛" foam. It also had the jump between ⅛" and ¼" foam. It then plateaued slightly but showed a subtle increase between the ¼", ½" and 1" foams. These results with be expanded upon in the discussion.

DISCUSSION

The expectation was that as foam thickness increased, the percent change of α would also increase. A change in the α value denotes a change in the type of noise behavior of the COP time series. Since the COP of a healthy person over time behaves as pink noise when analyzed, it is important to see how the α value changes as that person becomes "diseased" (i.e., has thicker foam placed under their feet). Varying from pink noise to white or brown noise means that the body is no longer behaving healthily. If the α value changes with respect to an increase in foam thickness, it can be expected that the α value would change also with an increase in a somatosensory deficiency in a patient. No statistical significance tests were performed on the results; thus, the discussions below indicate potential trends or conclusions.

Eyes open, anteroposterior direction

The 1/8" foam showed almost no change from the no foam control. This was observed in every other condition except for EC, in the ML direction. The small change either means that 1/8" foam is so small that it did not have an effect on the healthy subjects in the study or small somatosensory deficiencies are not detectable through these methods. The ~5% change between 1/8" and ¼" foam shows that a minor deficiency could be tracked using these methods. The ¼", ½", and 1" foam did not show changes between each other. Therefore, for this condition, the increasing foam thickness was not a good approximation of increasing "disease."

Eyes open, mediolateral direction

The 1/8" foam data point shows the same results as the EO, AP direction. The small change leads to the same conclusions as previously mentioned (foam being too small to make an impact or is not detectable). The ¼", ½" and 1" foam points create a linear trend that shows that as the foam thickness increases, the percent change of α from the no foam control increases. These results perhaps show the most potential for somatosensory diagnosis. First, the jump from 1/8" to ¼" foam, shown in other conditions, shows potential for early diagnosis. Secondly, the continual increase shows the potential to diagnose the severity of the deficiency as well. For example, this means that an analysis of the α of a patient could not only show that they have a somatosensory deficiency but also show just how extreme it is.

Eyes closed, anteroposterior direction

The results of the 1/8", ½", and ¼" foam points are similar to the corresponding points in the other conditions discussed previously. The 1" foam data point is the most intriguing of all the points. As discussed earlier, a thicker foam is expected to create a greater change in α. However, in this condition, the percent change of α from F_0 decreased between ½" and 1" foam. This result is difficult to explain. For now, this data point is inexplicable, so more research is needed to support this finding and eventually find its cause.

Eyes closed, mediolateral direction

The 1/8" foam under this condition was different from all of the other 1/8" foam data points in the other conditions. It had a substantial change from F_0. There was also an increase from 1/8" to ¼" foam. This implies that this condition shows the largest potential for early diagnosis. Along with the jumps seen, the magnitude of the percent change was greater than all the other conditions. The ½" and 1" foam points did not show much change from the ¼" point. However, at 1" foam the percent change of α from F_0 is ~8%. This means that this condition shows the potential to aid in the diagnosis of more severe somatosensory deficiencies. Thus, testing a patient using a force plate with their EC and analyzing the COP in the ML direction could be used to diagnose a severe somatosensory deficiency.

CONCLUSIONS

Using DFA on the COP of time series shows potential for early somatosensory deficiency. This is supported by multiple conditions showing a larger percent change on smaller foams, specifically the 1/8" foam. In addition, the EO, ML direction condition shows the potential to diagnose not only the existence but the severity of a somatosensory deficiency. Using nonlinear measures on the COP time series shows the feasibility of analyzing this complex data.

Using other nonlinear measures than DFA would provide a further understanding of the data. One study used multiple nonlinear measures to analyze COP in a sitting subject [17]. These measures (Lyapunov Exponent Correlation Dimension and Approximate Entropy) could also be used to analyze the data in this study. Any nonlinear measure to interpret the data could be beneficial to give a bigger picture to understand postural stability.

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