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In-Home Measurement of the Effect of Strategically Weighted Vests on Ambulation

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Abstract: **Strategically weighted vests are currently being used to treat patients with Parkinson's, Multiple Sclerosis, and ataxia. While studies have been conducted to demonstrate the effectiveness of these vests, there has been very little research into the mechanisms that give rise to the vest's results. This study demonstrates the ability to capture gait parameters from depth images[1] in the home with sufficient sensitivity to support future investigation of the weighted vest intervention. The study also explores multiple metrics, using in-home gait sensing, to study a subject's ambulatory ability including gait mechanics, uncertainty in motion, and gait cadence. We then investigate the effects of these vests on a subject's ambulation by examining these metrics both before and after the vest is worn. While only four subjects were used, results are promising, showing a statistically significant and clinically significant change in many of these metrics as a result of the vest. The cases presented here concern two subjects, one with a "tight" gait caused by Progressive Supranuclear Palsy, and the second with an excessively "loose" gait due to Parkinson's disease. We show that in both subjects, using the vest immediately moved the metrics in a direction beneficial to the subject's clinical condition. This result concurs with clinical observations as measured using various clinical fall risk instruments.**

I. INTRODUCTION

Strategically weighted vests are currently being utilized to treat patients with multiple sclerosis, Parkinson's disease, and ataxia. One such BalanceWear® vest, produced by Motion Therapeutics in Oxnard, CA, consists of a vest, worn on the torso with Velcro areas where small, light weights are attached. The physical therapist performs the Balance-Based Torso-Weighting™ (BBTW) balance assessment on the patient to identify directional imbalance of a subject and strategically places ¼ to ½ pound increments of weight in specific locations on the vest to improve balance and postural control. The patient is then instructed to wear the vest for several hours once or twice during the day. Studies conducted have focused on the clinical effects of the vest [2-4] but have not started to investigate how the vest specifically impacts the patient's ambulation beyond gait speed.

In this paper, we investigate whether the in-home capture of gait can be measured with sufficient sensitivity to support future investigation of the weighted vest intervention. The ultimate goal is to study the underlying mechanisms of the intervention in a larger study.

The remaining sections of this paper begin with a brief discussion of background work. The Methods section describes how the data was collected and analyzed. Finally we will show the results obtained and discuss our findings.

II. BACKGROUND

A. *Studies with the Strategically Weighted Vest*

While there is some published research being conducted on the use of strategically weighted vests in other applications, there has been little to no research, outside of the studies referenced above, on the usefulness of these vests for improving the ambulation and reducing the risk of falls in the elderly. In [2], the author presents the case of a single patient who experienced improved balance and gait during static and dynamic activities. In [3], the authors expand upon the previous study to include 16 subjects with Multiple Sclerosis and found significant improvement in several clinical assessments of balance. The last study [4] was a full clinical trial demonstrating immediate improvement of gait velocity and functional activity. To date, no research has been found that studies the mechanisms by which the vest intervention improves a subject's ambulation.

B. *Entropy*

Entropy measures the irregularity or randomness in a signal; here, we compute entropy to measure the randomness or irregularity in gait. We assume that a healthy walk, when decomposed into three orthogonal directions, is a fairly regular sinusoid with a period equal to the stride time. Conversely, higher entropy values suggest higher random variability in gait, an indication of heightened risk of falling. Our hypothesis is that as a person's ability to balance or walk unassisted declines, that person's walk would show an increased unsteadiness and, consequently, higher entropy. Arafat used entropy to study gait deficiencies and to identify ataxia in horses[5]. In his work, he utilized three different computations of entropy. The first, equation 1, by Deluca and Termini in 1972 [6], is given by:

$$H_{DTE}^{\mu_k} = -K\sum_{j} \mu_{kj} log_2 \mu_{kj} + (1-\mu_{kj}) log_2 (1-\mu_{kj})$$

Equation 2, developed by Pal in 1989 [7]is given here:

$$H_{PPE}^{\mu_k} = K\sum_{j} \mu_{kj} e^{1-\mu_{kj}} + (1-\mu_{kj}) e^{\mu_{kj}}$$

And equation 3, developed by Pal & Bezdek in 1994 [8]:

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$$H_{\alpha QE}^{\mu_k} = K\sum_{j} \mu_{kj}^{\alpha} + (1-\mu_{kj}^{\alpha})^{\alpha}$$

In all three formulae, μ_{kj} is the fuzzy membership of each data point, C_{kj}. K is a normalization constant taken to be 1 in each of these measurements.

III. METHODS

A. The Weighted Vest

The vest was weighted in accordance with Motion Therapeutics' recommended BBTW assessment approach. The subject was evaluated for proper balance and small weights were chosen, along with the proper location for these weights. Following the assessment, the subject was instructed to wear the vest twice per day for two hours each session, though subjects often wore it for longer or shorter periods of time. With staff assistance, the subject recorded when the vest was put on or taken off. The balance assessment was repeated every 2 weeks and the amount of weight and locations were adjusted as needed. Clinical fall risk assessments were also performed at this time.

B. Data Collection

With approval from the University of Missouri IRB, a Microsoft Kinect system was placed in the apartments of four subjects. Subjects were chosen based upon their current physical condition and likely benefit of the weighted vest therapy. Depth image data are used directly as in previous work[9, 10]. The system collected and stored the centroid location at 5-15 frames per second for each object that moved throughout the room. Centroids were computed as an average of segmented depth images [11]. These "paths" are then culled to remove those paths that do not correspond to a straight line walk for a minimum distance. This was done to remove the effects of turns, pauses, and other features of typical day-to-day activities that do not represent purposeful walks.

As described above, the resident periodically donned and doffed the vest while recording the time it was done. Otherwise, the subject activities were unrestricted.

The camera system was active 24 hours per day in the living room of each apartment, and any walks made during that time were captured. Data were captured for roughly 120 days for each subject.

C. Data Analysis

1) Pre-processing

After adjusting to a fixed 15 frames per second sampling rate (averaging multiple points and interpolating missing points), the centroid data are first transformed from room oriented x,y,z coordinates into a triplet of error values $e_x, e_y,$ and e_z where the error values are the deviation from the expected location along the walking path. The expected location is found by projecting a best fit line over 1 second centered on the current point in time and extending it to the next frame. The error in the X direction is the difference between the actual location and the expected location in the direction of travel. The error in the Y direction is the similar difference perpendicular to the direction of travel and parallel to the floor (*i.e.* lateral movement). Finally, the error in the Z direction is the difference in the vertical direction. The last pre-processing step removes those walks not likely to be from the subject by using a k-means clustering algorithm to filter any samples that are more than 0.9 standard deviations from the cluster center. Clustering is performed on height and walking speed.

2) Calculation of Metrics

After pre-processing, the following metrics are computed using the error values generated.

- Asymmetry is computed in all three directions as the ratio between the mean error ($\overline{e_i}$) and the maximum error for a given walk (i = x, y, or z). This measures the degree to which the walk favors one side versus the other.

$$asymmetry = \frac{\overline{e_i}}{MAX(|e_i|)}$$

- Peak-to-Peak is computed in all three directions as the difference between the largest error values in both the positive and negative directions.

$$p2p = MAX(e_i) - MIN(e_i)$$

- Entropy is computed in all three directions as the average of the results of equations 1-3 shown above.

$$H = \left(H_{DTE}^{\mu_k} + H_{PPE}^{\mu_k} + H_{\alpha QE}^{\mu_k}\right) \div 3$$

3) Measuring Effects of the Strategically Weighted Vest.

For a given metric, the time relative to each time the vest is donned ("vest on" event) or doffed ("vest off" event) is computed. These relative times are then binned into 40 bins and the average of each bin is computed. The bin width is chosen to maximize the visibility of the vest's effects. If the chosen bin width is too narrow, then the complete effect of the event will not be visualized. If the chosen bin width is too wide, there will be some longer term effects that may hide the direct effects of the vest. As our purpose for this study was to demonstrate the ability to measure a change in ambulation when the vest is donned and doffed, window sizes were chosen to maximize the change for the most metrics. This was done by scanning 50 different window sizes from 0.375 minutes up to 18.75 minutes in 0.375 minute steps and selecting the window with the largest number of metrics showing a significant change.

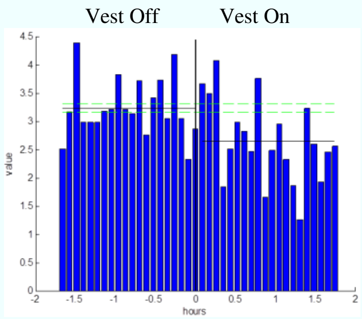

Figure 1: Plot showing Peak-to-Peak motion in the Z direction. Window size is 3 ½ hours. Horizontal axis shows time relative to the event, noted by the vertical line. Vertical axis shows the average motion in inches. Solid, horizontal bars represent the means before and after the event. Dashed lines correspond to +/- 1 MDC.

The average values of the metric in each bin are then plotted. A sample plot is shown in figure 1. The distribution both before and after the event are tested to determine if they are drawn from a Gaussian distribution using the t-test. If they are Gaussian, then the t-test is used to test the hypothesis that the two sets of data are selected from different populations. If they are not Gaussian, then the Rank-Sum test is used instead.

Lastly, the Minimum Detectable Change (MDC) is computed using the approach defined in [12]. This step is skipped for pre-event distributions that are not Gaussian or have a strong correlation with itself ($\rho > 0.50$). The computation is a two-step process using the following formulae. The first step is to compute the statistical "t" value using the following:

$$t = \frac{\overline{\mathrm{X}}_{\mathrm{pre}} - \overline{\mathrm{X}}_{\mathrm{post}}}{\mathrm{S}_{\mathrm{X}_{\mathrm{pre}}\mathrm{X}_{\mathrm{post}}}\sqrt{\frac{1}{\mathrm{n}_{\mathrm{pre}}} + \frac{1}{\mathrm{n}_{\mathrm{post}}}}}$$

Where

$$\mathrm{S}_{\mathrm{X}_{\mathrm{pre}}\mathrm{X}_{\mathrm{post}}} = \sqrt{\frac{(\mathrm{n}_{\mathrm{pre}} - 1)\mathrm{S}^2_{\mathrm{X}_{\mathrm{pre}}} + (\mathrm{n}_{\mathrm{post}} - 1)\mathrm{S}^2_{\mathrm{X}_{\mathrm{post}}}}{\mathrm{n}_{\mathrm{pre}} + \mathrm{n}_{\mathrm{post}} - 2}}$$

and $\overline{\mathrm{X}}_{\mathrm{pre}}$ and $\overline{\mathrm{X}}_{\mathrm{post}}$ are the means for the pre-event distribution and the post-event distribution respectively. $\mathrm{n}_{\mathrm{pre}}$ and $\mathrm{n}_{\mathrm{post}}$ are the number of samples in the pre- and post-event distributions. $\mathrm{S}^2_{\mathrm{X}_{\mathrm{pre}}}$ and $\mathrm{S}^2_{\mathrm{X}_{\mathrm{post}}}$ are the variances for each distribution. Finally, MDC is computed using the following formula:

$$MDC = t\sqrt{\frac{MSE}{n_{pre}} + \frac{MSE}{n_{post}}}$$

where MSE is the pooled mean squared error which is estimated by the variance for the pre-event distribution.

TABLE I

Results showing changes in gait metrics for vest on and vest off events. Entropy and Asymmetry are unit-less. Statistically significant changes in ***boldfaced*** *type.*

Metric	Subject #1		Subject #2	
	Δ Vest On # MDC's	Δ Vest Off # MDC's	Δ Vest On # MDC's	Δ Vest Off # MDC's
Asymmetry X	**-0.023** **1.45**	**+0.049** **9.20**	**+0.0034** **2.581**	**-0.0031** **66.00**
Asymmetry Y	-0.013 0.473	-0.0074 0.289	**-0.0214** **1.200**	+0.0004 0.0258
Asymmetry Z	**-0.0059** **22.61**	**+0.016** **9.67**	**-0.0034** **3.260**	**+0.0136** **45.94**
Entropy X	**-0.99** **4.50**	**+2.35** **33.14**	**+0.196** **1.090**	**-0.343** **3.404**
Entropy Y	**-0.87** **2.18**	**+1.52** **2.55**	**-0.368** **1.852**	**+1.184** **12.88**
Entropy Z	**-0.63** **5.16**	**+1.62** **14.4**	+0.036 0.42	**-0.162** **1.848**
Peak to Peak X (inches)	**-0.51** **8.07**	**+1.32** **34.2**	+0.0172 0.269	**-0.160** **4.20**
Peak to Peak Y (inches)	**-0.32** **1.21**	**+1.00** **71.2**	**-0.518** **1.81**	**+0.644** **4.087**
Peak to Peak Z (inches)	**-0.57** **7.54**	**+1.50** **22.1**	+0.0229 0.450	**-0.113** **1.726**

IV. RESULTS

Table 1 shows the results for a select group of metrics for two subjects. For brevity, the remaining subjects, with similar results to what is presented, are not included in this paper. Each cell shows the change in the metric (top value) and the number of MDC's the change represents (bottom value). These results show a definite and statistically significant positive effect on several metrics for each of the subjects. It is also apparent from the results that the effect of the vest varies from subject to subject.

A. *Subject #1*

This subject has a stiff, ridged gait, due to Progressive Supranuclear Palsy. As a result, one would expect more exaggerated motion in all three directions. For this subject, the results show significant improvement in nearly all of the metrics presented when the vest is donned as well as a rebound past the initial value when the vest is removed. When the vest is put on, the Peak to Peak Z value drops by 0.57 inches. When the vest is removed, the metric value increases by 1.5 inches showing at least a short term rebound.

Looking at the entropy in the subjects walk, we expect to see a reduction in entropy as the vest is donned, and an increase when the vest is removed. When the vest is donned, the entropy in the X, Y and Z directions decrease by 0.99 (4.5 MDC's), 0.87 (2.18 MDC's), and 0.63 (5.16 MDC's) respectively. When the vest is removed, the entropy increases by 2.35 (33.1 MDC's), 1.52 (2.55 MDC's), and 1.62 (14.4 MDC's) for X, Y, and Z respectively.

Looking at asymmetry in all three directions, one can see a reduction in the X and Z directions when the vest is donned suggesting less asymmetrical movement in the dorsal/ventral or rostral/caudal directions. The Y direction also seems to be trending downward but the change is not significant. When removed, both metrics show a rebound beyond the initial values in the X and Z directions and virtually no change in the Y direction.

B. *Subject #2*

Subject #2 has a Parkinson's disease which results in a very "loose" gait. For this subject, the vest does not decrease peak-to-peak motion as was seen in the first subject. For the X and Z directions, while there was not a statistically significant change, there was a trend towards an increase in these parameters. A positive change in peak-to-peak motion may suggest a "tightening" in the subject's gait. In the Y direction, there is also a decrease in peak-to-peak motion similar to subject #1. Since this subject's gait is "looser" than the first subject, one would not expect to see a large decrease in peak-to-peak motion.

For entropy, this subject's results show an increase in the X direction and Z direction but in the Y direction, entropy decreases as it does with subject #1, although not as significantly.

For asymmetry, the results show a slight increase in the X direction, followed by a decrease by nearly the same amount when the vest is removed. In the Y and Z directions, on the other hand, the results show a decrease when the vest is put on, and an increase (though not significant for Y) when the vest is removed.

Overall, for all three metrics, there was a slight decrease (no greater than 2.2 MDC's) in the Y direction for both subjects when the vest is removed. For the remaining metrics and directions, only asymmetry in the Z direction shows similar behavior with the remainder showing a decrease for subject #1 and an increase for subject #2.

V. DISCUSSION

The results presented lay the ground work for further study of the mechanical and physiological effects of the strategically weighted vest. They also demonstrate several metrics that can be used to explore the effects of the vest on the subject's ambulation. The first subject had a very tight gait (imagine the extreme case of walking without bending your knees) so you would expect peak to peak values to be higher than typical with more randomness. When the vest is put on, all three metrics, in all three directions show either a significant change or at least a trend towards a change conducive with improved ambulation.

The second subject, with a looser gait, showed a much less pronounced change in both entropy and peak-to-peak movement. Also, smaller, though more significant, changes were seen in both the X and Y directions for asymmetry. With a loose gait you would not expect to see significant reductions in peak-to-peak motion. In the case of this subject, it is harder to see the effect of the vest with these three metrics.

Looking specifically at entropy and peak-to-peak motion, both metrics showed similar behavior. Subject 1 showed significant reduction in both metrics in the X and Z directions suggesting less motion in these directions and, possibly, less rigidity in her ambulation. Subject #2, on the other hand, showed a much less dramatic change suggesting that for this subject, the observed clinical improvement was in asymmetry or, perhaps, other areas.

One other aspect that invites further study is the behavior in the Y direction. For entropy and peak-to-peak metrics, the X and Z directions showed changes in the same direction for a given subject, and opposite directions between subjects. However, in the Y direction, donning the vest resulted in a decrease in these metrics over both subjects. While the weights used on the vest are not significant (< 1 kg), one could envision that carrying the increased weight causes less motion in the Y direction and, as a result, less irregular motion in that direction.

As the efficacy of BBTW technology and BalanceWear Orthosis continues to be studied and validated, and Physical Therapy testing during the study confirmed the improvement of each subject. These results suggest that the changes shown in the bulk of these parameters are in the right direction and that, as one might expect, the ideal values are somewhere in between subject 1 and subject 2.

The optimum bin width was shown to be unique for each of the subjects studied. It is not clear, as of now, if the variability is due to the patient's disease or simply unique to each particular person. Further study with other similarly afflicted subjects, as well as more metrics, would help answer this question.

Lastly, and most importantly, these results show that through continuous in-home monitoring using our Kinect-based gait analysis system, it is possible to extract metrics that can be used to characterize a subject's ambulation. We can currently measure entropy, asymmetry, and peak-to-peak motion. This on-going project is currently developing algorithms to measure cadence related metrics including stride-time, and stride length for both left and right leg, trunk sway, and others as done in prior work [1, 9, 10].

VI. CONCLUSION

We have demonstrated a measurable effect of strategic weighting on the gait of two subjects using continuous in-home monitoring of the subject's gait. The effects are measured through different metrics that characterize the mechanical aspects of gait, the regularity, and the symmetry that define how the subject walks. This will serve as a good springboard for more detailed analysis of the effects of the vest in particular and for quantifying human gait in general.

In addition to the ongoing work in developing these metrics, future work will include additional subjects for whom data is currently being collected.

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