THE EFFECTS OF FATIGUE AND VISUAL PERTURBATION ON POSTURAL CONTROL IN HEALTHY POPULATIONS

by

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Abstract

The sensorimotor system is crucial in maintaining postural control. This study looked at it. Many studies have looked at how muscular fatigue and visual perturbation affect the sensorimotor system using a force plate to collect center of pressure (CoP) data. This study sought to look at the combined effects of fatigue and visual perturbation using virtual reality (VR) to evaluate changes in non-linear CoP measures using Novel Pedar technology. CoP data was collected for six healthy young adults using a Bertec force plate and the Novel Pedar X insole pressure system in quiet stance. This was done in a non-VR condition (NVR) and a VR condition (YVR) where participants were placed into a moving room. These measures were taken before and after a muscular fatigue task that involved walking on a treadmill at a gradually increasing incline. Sum of CoP path, 95% ellipse area (EA), virtual time-to-contact (VTC) minima, and VTC minima coefficient of variation (VTC min COV) were taken and compared for pre- and post-fatigue, NVR and YVR, and the interaction between the two. Results showed a significant decrease VTC min COV ($p < 0.05$) as a result of fatigue. The YVR condition was able to create a significant increase in the sum of CoP path and VTC min. When looking at the interactions, it was determined that fatigue increased the VTC min for the NVR condition and decreased it for the YVR condition. It also showed a significant increase in the sum of CoP path, given pre- and post-fatigue. The results showed that both fatigue and visual perturbation created a change in postural control that increased CoP movement but allowed it to be more controlled. The force plate and Pedar data varied greatly, and usually only one collection technique detected significant differences between the main effects. Overall, gave varying results on how they affected postural control.

1. Introduction

The sensorimotor system is how the body maintains balance. The brain uses proprioception and the visual information it receives to make adjustments to a person's position, which is called postural control. Even in quiet standing the body makes minor adjustments to maintain an upright posture (AlGhali et al., 2023). These minor adjustments can be evaluated using center of pressure (CoP) measures. CoP is the average point where a person's force is concentrated on the ground (AlGhali et al., 2023). The pressures are recorded as coordinates in two one-dimensional planes called anteroposterior (AM) and mediolateral (ML) (Quijoux et al., 2021). As a person shifts their weight the coordinates for where the CoP is will change.

This study sought to determine if postural control is altered by muscular fatigue. In addition, we examined whether visual perturbation exacerbated these effects since there is a large visual component to the sensorimotor system.

1.1. Fatigue

Fatigue is something every individual experiences. Therefore, it is valuable to know what kind of effects it has on the sensorimotor system. Beurskens et al., (2016) showed that fatigue affects balance even in static standing. CoP measures (displacement, velocity, and sway area) increased significantly when 80% maximum fatigue was reached, which indicates a decrease in postural control. They cited that this can be due to changes in peripheral activity, thus pointing to a decrease in the nervous system's ability to regulate muscle movement. Vitiello et al., (2016) similarly showed that CoP length increased after walking on a treadmill for 15 minutes. This shows that there is a connection between muscular fatigue and postural control that can be looked into further.

1.2. Visual Perturbation

The ability to balance depends on the combination of many aspects of the body and the brain. Visual cues are a large part of how one understands how they are oriented in space (Horak, 2006). When vision is altered, balance is negatively affected because the sensorimotor system takes in the visual information and integrates it into postural control.

Previous studies have shown that having participants close their eyes is enough of an alteration to create a statistically significantly larger sway area, as seen by Johansson et al., (2019), where there was statistical significance for sway area and limits of stability between eyes open and eyes closed in a quiet stance; however, we wanted to see if there was a better visual challenge for CoP. This study tested individuals' postural control via an eyes closed (EC) condition and by placing them in a virtual reality moving room (MR). Heidner et al., (2020) determined that VR technology allows for visual perturbation to be amplified while allowing participants to still feel like they are in a real-world environment. This study determined the best frequency and amplitude for anterior-posterior sinusoidal motion for a VR moving room. They determined that a higher amplitude and a frequency of 0.5 Hz was best to test balance. Therefore, their setup was replicated for the VR moving room condition of this study. Our expectation is that the MR will create an even stronger challenge than the eyes closed condition, thus allowing us to further see how visual perturbation affects postural control alongside muscular fatigue.

1.3. Novel Pedar

Many postural control studies have looked at the effects of fatigue, but most of them use a force plate to gather data. This study will collect postural control information from the force plate as well as the Novel Pedar in-sole pressure system, which is essentially a wearable, mobile force plate. A handful of articles have validated the accuracy of center of pressure direct measures for the Pedar insoles, but none have used them to evaluate sway area or virtual time-to-contact. Literature was helpful in determining the best practice for using Pedar. For example, Debbi et al., (2012) discovered that the axes of the force plate needed to be adjusted to each foot in order to match how Pedar processes data. This study will add to what is known about this relatively newer technology because, if done properly, it provides a way to collect CoP data without having to be in a physical lab.

1.4. CoP Measures

CoP is determined by how force is distributed over different coordinates. From this, we can gather both linear and non-linear CoP movements. The linear measure we focused on was sum of CoP path, which shows the total distance of movement. Higher measures indicate less balance (Heidner et al., 2020) because the individual is moving more, which points to instability. One non-linear measure was 95% confidence ellipse area (EA), which is also known as the sway area. This is a perimeter that encircles where a person's CoP is 95% of the time. The larger the area, the more they move. The other non-linear measure was virtual time-to-contact (VTC). This creates an even wider perimeter in a similar process to how the 95% EA is made.

VTC determines how long it would take an individual to hit the boundary at the rate of their sway, therefore, a smaller value indicates less balance because it would take the individual less time to reach the boundary (Whittier et al., 2020). A study by Slobounov et al., 2008 showed a statistically significant change in mean VTC min and mode, whereas linear COP measures showed no change, thus pointing to VTC's increase in sensitivity to postural control. VTC naturally rises and falls as an individual sways, so VTC minima (VTC min) is the average of the lowest points. VTC min indicates a change in movement to prevent falling, and therefore creates a more detailed picture of an individual's postural control (Whittier et al., 2020). From these minimums, a coefficient of variation (COV) can be found. The VTC min COV shows how closely the data follows the estimated mean. A smaller COV concludes that the VTC fluctuated less (*Coefficient of variation*).

1.6. Purpose of Study

The focus of this study is to look at the effects of fatigue on the postural control of healthy individuals. It will also determine if any visual conditions exacerbate the effects of fatigue. It is predicted that CoP measures will indicate a decrease in balance post fatigue and that visual conditions, such as the moving room will additionally decrease balance. In addition, this study will serve to validate the accuracy of the CoP measures collected by the Novel Pedar in-sole pressure system by comparing them to force plate values.

2. Materials and methods

2.1. Participants

Six healthy young adults (ages 18-27), with an average weight of 153.7 lbs +/- 23.2 and a height of 67.3 inches +/- 3.7, were participants in this study. There were five females and one male. They had no medical conditions that would cause an interference with their ability to balance, such as a prior or current concussion, lower limb condition, or vision problems that could not be corrected with glasses. All but one of the data collections happened from eight to eleven in the morning. The study was approved by East Carolina University and Medical Center Institutional Review Board. Before data collection, all subjects gave written informed consent.

2.2. Measures

CoP measures were taken using an in-ground Bertec (Bertec, Columbus, Ohio) force plate and the Novel Pedar-X in-sole pressure system (software 23.8.7). The force plate used a AM6540 amplifier with a sample rate of 2500 Hz, and Pedar's sample rate was 100 Hz. Sum of CoP path, EA, VTC min, and VTC min COV were evaluated for both the force plate and the Pedar insoles.

2.3. Procedure

The study was explained to participants, and they signed and were offered a copy of the informed consent. They took a survey to verify that they did not have any of the exclusion health criteria. Height and weight were taken, and a Polar heart monitor was placed under their sternum. Then, they were fitted into a flat pair of shoes with their appropriate Pedar insole size. Participants stood on an in-ground force plate, and an X was placed on the television in front of them to give them a point to focus on. Participants were informed to stand still and look at the X. The pre-test consisted of three rounds of standing on the force plate for 30 seconds with their eyes open and 30 seconds with their eyes closed (EC), which together created the no-virtual reality condition (NVR). Then, they put on an HTC VIVE virtual reality headset, which placed them in a visual replication of the lab environment that was taken using a 360-degree camera. They were given the same instructions as before and did three rounds of 30 seconds in the still VR room, 30 seconds in the moving room (MR), and 30 seconds in recovery after the moving room. This created the YVR condition. The moving room moved anterior to posterior at 0.5 Hz at an amplitude of 20 cm since that produces the highest level of postural sway (Heidner et al., 2020). The Pedar insoles were recalibrated between the NVR and YVR portions. Then, they underwent a treadmill fatigue protocol, where they walked at a speed of 3.2, if they were under

5’8”, or 3.6, if they were over 5’8”, and went up one grade each minute. Fatigue was considered reached when the participant reached a rate of perceived exertion (RPE) of 13 or 76% of their target heart rate. The post-test used the same protocol as the pre-test.

2.4. Data reduction

The CoP force plate data was exported from Qualisys Track Manager (QTM) software (Qualisys, Goteborg, Sweden) and the Pedar data was collected through its own software (23.8.7). A MATLAB script was used to analyze the CoP displacement, velocities, and accelerations in the anteroposterior (AP) and mediolateral (ML) directions. It does this by aligning data from the force plate and the insoles and finding where there is data dropout via interpolation. Pedar’s CoP was found by calculating the left and right insole paths from a standardized coordinate frame and then combining them. The force plate CoP was calculated from one origin point in the bottom left corner. From here, the linear and non-linear measures can be calculated.

The sum of CoP path was determined by adding all the Eucidean distances from consecutive points. The 95% confidence EA was calculated from going two standard deviations away from the mean CoP displacement in both directions. VTC was calculated for each instant CoP position, acceleration, and velocity to create a virtual trajectory point for each. From this, the average VTC min and VTC min COV were found.

2.5. Data analysis

Data was analyzed using a repeated measures ANOVA. The series of ANOVAs looked at pre-fatigue vs post-fatigue as well as NVR vs YVR for Pedar and the force plate. Interactions were run between pre-/post-fatigue and NVR/YVR. The data was also analyzed for correlations between Pedar and the force plate.

Results

The average time spent on the treadmill was 5:50 min +/- 2:19. Three participants stopped due to reaching an RPE of 13, and three stopped because their heart rate reached 76% of their age-predicted HR max.

ANOVA results for the sum of CoP path demonstrated a significant main effect of VR for the force plate [F(1,5) = 13.653; $p = 0.014$, $\eta 2 = 0.732$]. There was a significant increase between NVR (M = 1274.686, SD = 137.077) and YVR (M = 2366.316, SD = 412.517) (Figure 1). The ANOVA showed an interaction of [F(1,5) = 17.478; $p = 0.009$, $\eta 2 = 0.778$]. Sum of CoP path measured by Pedar, given NVR, was significantly different ($p = 0.002$) with pre-fatigue (M = 1234.835, SD = 516.993) and post-fatigue (M = 2034.226, SD = 516.993) (Figure 2). All pairwise comparisons were significantly different ($p < 0.05$) for both the force plate and Pedar when comparing NVR to YVR, given pre- and post-fatigue.

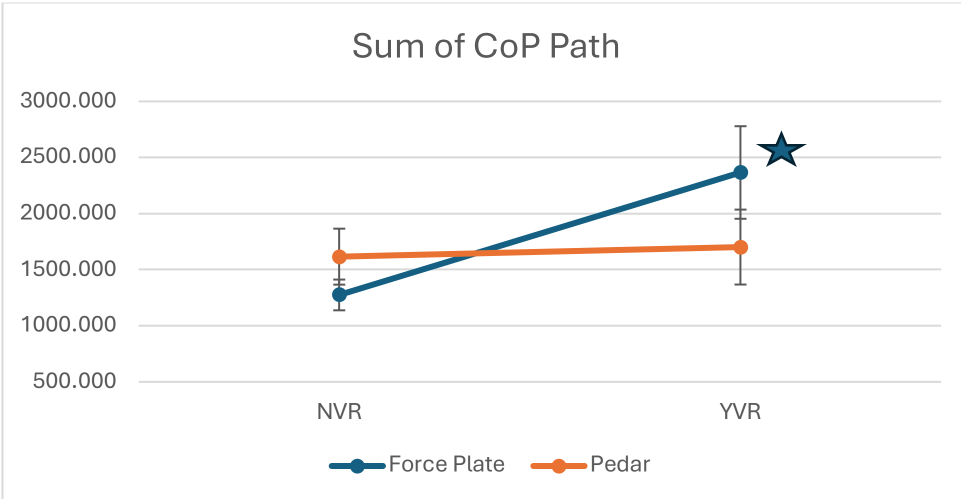

Figure 1: Comparing path length between visual conditions. The force plate showed a significant increase (p = 0.014)

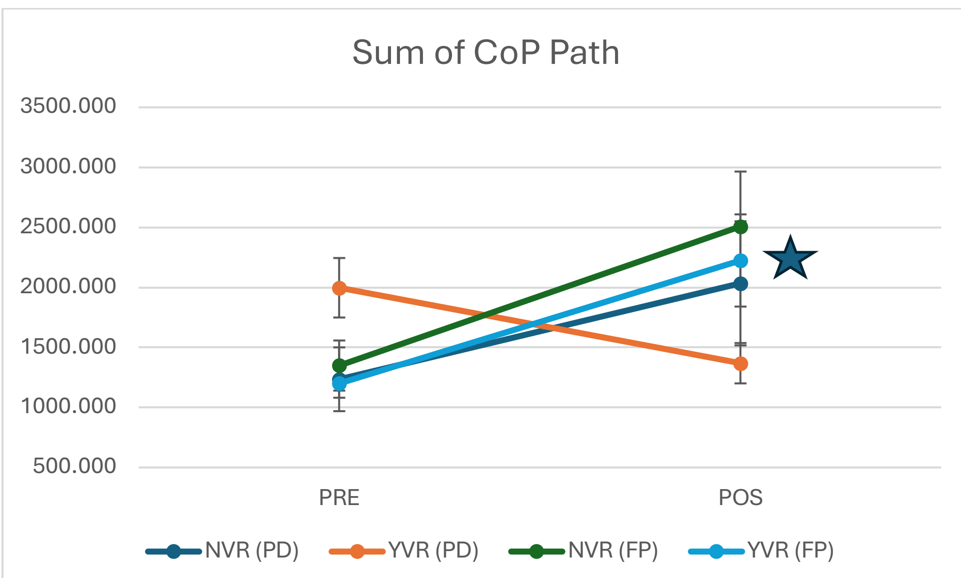

Figure 2: Comparing path length pre- and post-fatigue. Pedaar measured a significant increase (p = 0.002) during the NVR trial.

For VTC min, ANOVA revealed a significant main effect for Pedar of VR [$F(1,5) = 12.552$; $p = 0.017$, $\eta 2 = 0.715$] with an increase from NVR (M = 1.436, SD = 0.132) to YVR (M = 1.510, SD = 0.139) (Figure 3). It also showed a significant difference in interaction of Fatigue x VR for

Pedar [F(1,5) = 6.576; $p = 0.05$, $\eta 2 = 0.568$] and the force plate [F(1,5) = 8.037; $p = 0.036$, $\eta 2 = 0.616$] for VTC min. Given NVR, pre-fatigue (M = 0.700, SD = 0.097) was significantly different ($p = 0.020$) from post-fatigue (M = 0.606, SD = 0.048) as measured by the force plate (Figure 4). Pedar showed a significant difference ($p = 0.016$) when given pre-fatigue for NVR (M = 1.457, SD = 0.188) compared YVR (M = 1.589, SD = 0.211). When analyzing VTC min only for YVR, there was a significant main effect of [F(1,5) = 3.845; $p = 0.002$, $\eta 2 = 0.868$] (Figure 5).

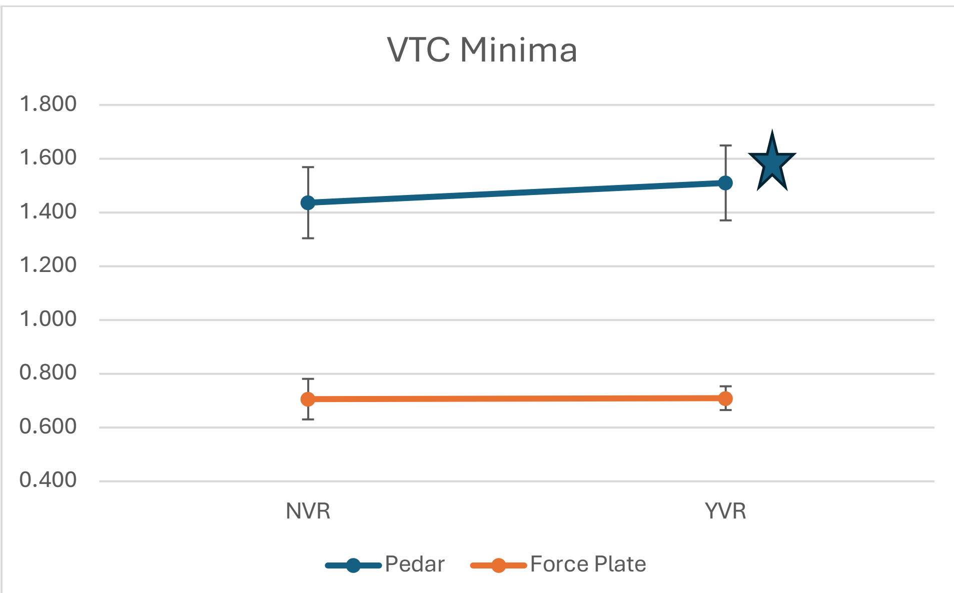

Figure 3: Comparing VTC min between VR conditions. Pedar showed a significant increase (p = 0.017)

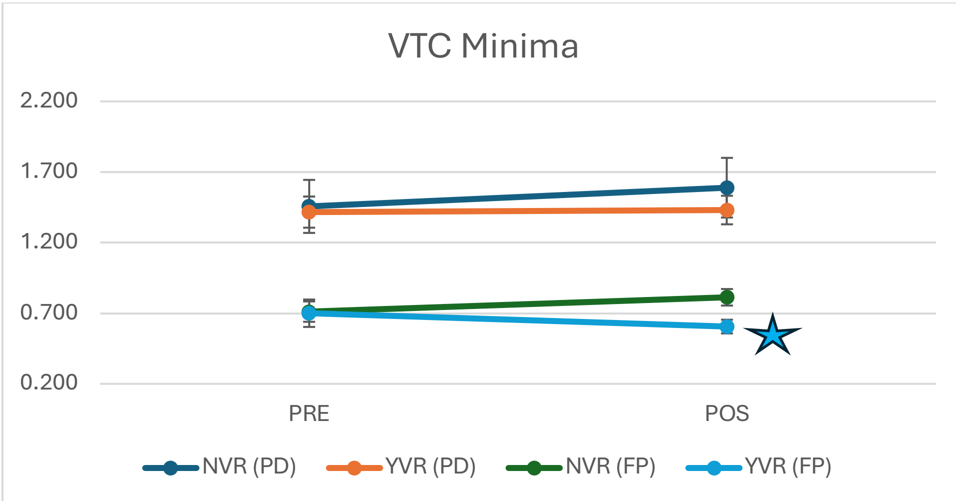

Figure 4: Comparing the effects on fatigue, given either NVR or YVR on VTC min. There was a significant decrease (p = 0.020) given YVR for the force plate.

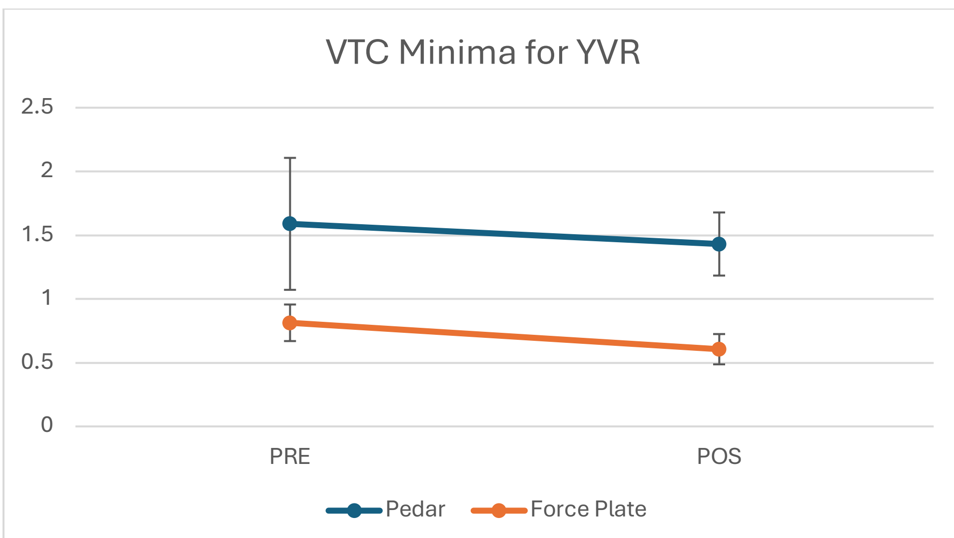

Figure 5: The change in VTC min caused by fatigue when only looking at YVR data. There was a significant decrease (p=0.002) when the data is combined. This shows it separated by data collection device.

ANOVA results for the force plate data displayed a significant main effect for VTC min COV of Fatigue [$F(1,5) = 7.915$; $p = 0.037$, $\eta 2 = 0.613$]. There was a decrease from pre-fatigue (M =

241.659, SD = 53.300) to post-fatigue (M = 124.862, SD = 14.368) (Figure 6). There was no significant difference in the main effects or interactions for ellipse area; in fact, pre- vs post-fatigue had an effect size of zero for ellipse area based on Pedar. Figure 7 shows an overlay of the data collected by the force plate vs Pedar (insole).

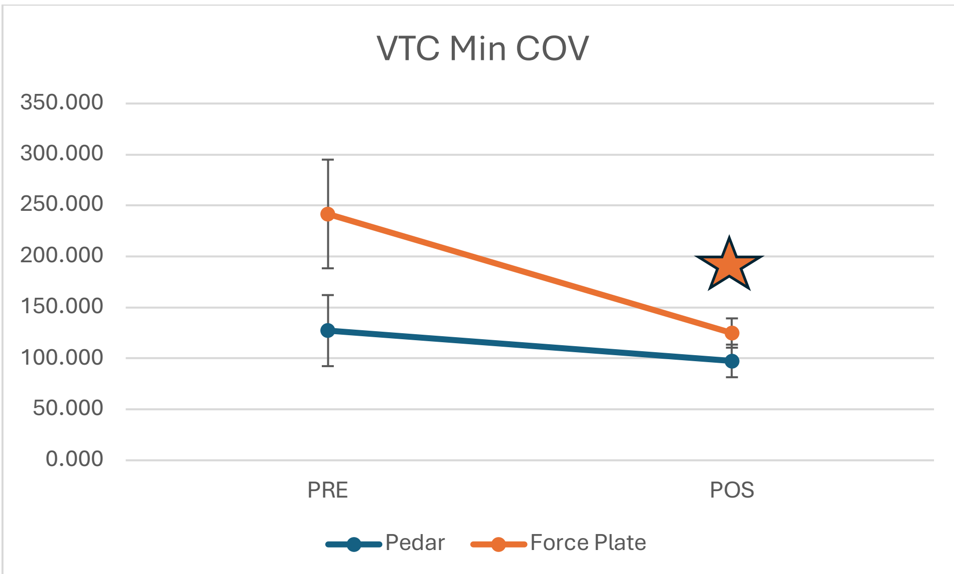

Figure 6: The effects of fatigue on VTC min COV. The force plate showed a significant decrease (p = 0.037).

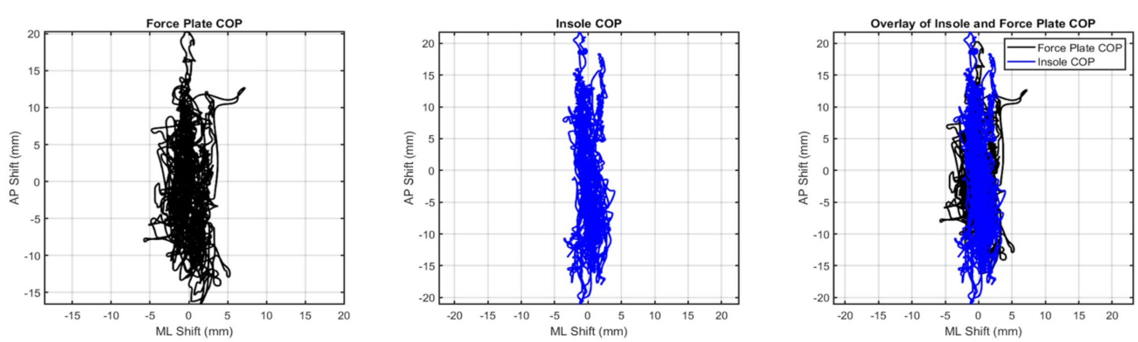

Figure 7: The CoP movement of one participant as collected by the force plate vs Pedar.

4. Discussion

The results show a mixed story due to the two different forms of CoP data collection. For every CoP measure, ANOVA shows a significant difference in main effect for either force plate or Pedar, but never both. There were only significant differences for both collection methods in the interactions between fatigue state and VR condition.

When comparing muscular fatigue states, the results showed a significant difference only in the VTC variables, which supports the findings of Slobounov et al., (2008) is more sensitive to changes in postural control than linear measures. When the ANOVA looked at fatigue state only as YVR, with Pedar and force plate combined, it displayed a decrease in VTC min in the post-fatigue state (Figure 5). This means it would take less time to hit the theoretical boundary. This followed the hypothesis that VTC min would decrease once muscles are fatigued because there is less postural control, causing an increase in velocity. The other measure to show a significant decrease when looking at fatigue was VTC min COV with the force plate data (Figure 6). A decrease in VTC min COV indicates that overall VTC did not fluctuate as much during post-fatigue. This was not expected, but helps demonstrate the complexities of postural control.

Our results showed a surprisingly low amount of effects on CoP from fatigue. Comparing the more linear measures to other literature, we see Vitiello et al., (2016) found no significant increase in EA, but a significant increase in sum of CoP path in neurotypical adolescents after a walking treadmill test. We agreed on the lack of EA difference, but our sum of CoP path as captured on the force plate had virtually no correlation to fatigue ($\eta 2$ = 0.009); however, Pedar had an effect size of 0.324. This once again points to the incongruencies of Pedar and force plate CoP capture. Meanwhile, Beurskens et al., (2016) showed a significant increase in EA ($p < 0.001$) for control vs fatigue. This is a sharp contrast to our results, which showed a significance of 0.649 on the force plate and 0.988 on Pedar. The conflicting results in all of these studies are likely because fatigue is not universally quantified.

The effects of visual perturbation are seen in the sum of CoP path and in VTC min. It was expected that YVR would show similar results as post-fatigue, however, this was not the case for VTC min. The post-fatigue state decreased, but the YVR condition increased when looking at Pedar (Figure 3). This would point to an increase in balance. This is surprising since the MR induces postural sway, but it could be because the MR sways in a consistent oscillating pattern, which allows for predictability versus the variability of shifting directions in the EC condition.

The sum of CoP path measured by the force plate increased significantly during YVR, which was expected (Figure 1). The purpose of the MR condition during YVR is to induce postural sway, so the increase in path length shows that MR creates more sway than the visual challenge of EC during the NVR trial. When analyzing the interactions between fatigue and VRR, ANOVA calculated a significant increase only when using Pedar data when comparing pre- to post-fatigue, given NVR and YVR (Figure 2), but comparing NVR to YVR, given pre- and post-fatigue, reveals a significant increase using both the force plate and Pedar data. Overall, all of the pairwise comparisons show an increase in sum of CoP path when going to YVR or post-fatigue, except that Pedar calculated that YVR is lower than NVR given post-fatigue, and post-fatigue is lower than pre given YVR. As stated above, these were the expected results since a higher sum of CoP path indicates less balance, and therefore occurs in the YVR and post-fatigue conditions.

The interactions between fatigue state and VR condition for VTC min paint the same picture as each main effect. When comparing pre- to post-fatigue, given NVR and YVR, the force plate had a significant decrease (Figure 4), and when comparing NVR to YVR, given pre-and post-fatigue, Pedar had a significant increase for Pedar. This reiterates that fatigue increases velocity, making it so the boundary is reached faster, and that the YVR condition inadvertently created an environment where balance could be maintained more easily.

No main effects or interactions were found to be significantly different for EA. This means that even though participants' sum of CoP paths were increasing from NVR to YVR, their EA wasn't. This means that even though they were moving more, the area they were moving in wasn't increasing. The lack of increase in EA during YVR could help explain why there was an increase in the VTC min, instead of the predicted decrease. There was an interaction between fatigue and VR with an effect size of 0.446 for Pedar data and 0.407 for the force plate data. This effect size is large, especially since the sample size was six. This is interesting that there is a large effect size during the interaction, since the effect size when only comparing pre- and post-fatigue with Pedar was zero, which would indicate that fatigue has no effect on ellipse area.

Beyond looking at fatigue and visual perturbation, this study wanted to compare CoP data from the force plate and Pedar. The device that found significant differences varied depending on the measure. The ANOVA that was run only using YVR data compared the force plate to Pedar and calculated a significance value of 0.063 and an effect size of 0.533. This is a large effect size, so even though it wasn't significantly different, there was still an appreciable difference between results. The in-ground force plate is the standard for measuring CoP, so Pedar collecting almost significantly different data is discouraging. There have not been prior articles published to our knowledge comparing Pedar and force plate using non-linear measures, so more research needs to be done to see if this is a consistent trend due to the differences in data collection and analysis between the two. Until more research is done, one should use caution if they decide to use Pedar for studies requiring in-field collection of CoP data that will be used for non-linear measures.

The results from this study can also be used in future studies using VR. The MR created an increase in sum of CoP path and VTC min. Therefore, if the desired result is to increase postural sway, MR is better than EC. However, if the goal is to create a visual challenge that causes the person to make more adjustments, thus increasing the VTC min and VTC min COV, the MR is not sufficient due to the repetitive nature of the oscillations.

There were many limitations when it came to Pedar. For one, Pedar and the force plate calculate CoP differently, which could be attributing to the wide variability found in the ANOVA results between the two. The force plate measures CoP coordinates from one point in the corner. Pedar calculates CoP for each insole and then combines them. Pedar can also only measure the force it collects in the area of each insole. When looking at ellipse area data, Pedar picks up less medial-lateral movement than the force plate because of the shape of the insole (Figure 7). Another limitation of using Pedar is that the software lacks the ability to place markers. This is why the results are broken down into NVR vs YVR instead of the five conditions done in the procedure. It would have been interesting to compare EC to MR, but without markers, this was not possible.

Limitations outside of Pedar include a lack of diversity in the sample. The study was approved for participants ages 18-50, however, only young adults participated. Also, participants may not have reached a high enough state of fatigue to see results due to the treadmill cutoff being an RPE of 13 or 76% of age-predicted HR max.

In conclusion, both fatigue and visual perturbation altered postural control. Fatigue increased the sum of CoP path and decreased the VTC min COV, thus indicating an increase in movement, but having less deviation from the center. Fatigue increased the VTC min for the NVR condition, while decreasing the VTC min for YVR condition. The MR in the YVR was able to induce a larger sway than EC as seen by the increase in sum of CoP path in the YVR condition, but the sway was slower and more controlled, hence the increased VTC min. Overall, sum of CoP path and VTC min picked up the majority of changes, looking at both fatigue and visual perturbation. This shows that there is valuable information about postural control in linear and non-linear measures. Additionally, this study created a lack of confidence in validating Pedar. There were frequently large, if not significant, differences in what data they collected. When considering the other limitations of Pedar, it's unlikely that Pedar would be used again for field work.

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