# The Effect of Backward Perturbation on Fall Outcomes in Ankle Foot Orthosis (AFO) and Functional Electrical Stimulator (FES) Users with Chronic Stroke

by

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ABSTRACT

Between 20%-30% of stroke survivors have foot drop. Foot drop is characterized by inadequate dorsiflexion required to clear the foot of the ground during the swing phase of gait, increasing the risk of stumbles and falls (Pouwels et al. 2009; Hartholt et al. 2011). External postural perturbations such as trips and slips are associated with high rate of falls in individuals with stroke (Forster et al. 1995). Falls often results in head, hip, and wrist injuries (Hedlund et al 1987; Parkkari et al. 1999). A critical response necessary to recover one's balance and prevent a fall is the ability to evoke a compensatory step (Maki et al. 2003; Mansfield et al. 2013). This is the step taken to restore one's balance and prevent a fall. However, this is difficult for stroke survivors with foot drop as normal gait is impaired and this translates to difficulty in evoking a compensatory step. To address both foot drop and poor compensatory stepping response, assistive devices such as the ankle-foot-orthosis (AFO) and functional electrical stimulator (FES) are generally prescribed to stroke survivors (Kluding et al. 2013; S. Whiteside et al. 2015). The use of these assistive devices improves walking speed, foot clearance, cadence, and step length of its users (Bethoux et al. 2014; Abe et al. 2009; Everaert et al. 2013; Alam et al. 2014). However, their impact on fall outcome in individuals with stroke in not well evaluated (Weerdesteyn et al. 2008). A recent study (Masood Nevisipour et al. 2019) where stroke survivors experienced a forward treadmill perturbation, mimicking a trip, reports that the impaired compensatory stepping response in stroke survivors in not due to the use of the assistive devices but to severe ankle impairments which these devices do not fully address. However, falls can also

occur because of a slip. Slips constitute 40% of outdoor falls (Luukinen et al. 2000). In this study, results for fall rate and compensatory stepping response when subjects experience backward perturbations, mimicking slips, reveal that these devices do not impair the compensatory stepping response of its users.

# DEDICATION

I dedicate this work to my family and friends for their continuous support, love, and care.

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To the Mastercard Foundation Scholars Program at Arizona State University for providing me with this opportunity.

## ACKNOWLEDGMENTS

Praise and thanks to God for the grace and strength to complete this work successfully. I would like to express my heartfelt gratitude to my research supervisor, Dr. Claire Honeycutt for her patience, motivation, and guidance throughout my research. It was a privilege and honor to have her as my supervisor. Most importantly, Dr. Honeycutt is more than just a supervisor; she is a mother to us all.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Significance

Falls are the leading cause of injury-related hospital visits in older adults, accounting for 54% of injury-related deaths for individuals aged 65+ in 2015. Moreover, the older adult population is expected to increase by 55% by 2030 (Haddad et al. 2019), significantly increasing the economic burden of falls, which was reported at $48.5 billion in 2017 alone (Florence et al. 2018). Compared to unimpaired adults, individuals with stroke are 1.77 times more likely to fall, occurring at a rate of 8.7 falls/person/year after being discharged from the hospital (Simpson et al. 2011). Falls often result in head, hip, and wrist injuries, with an estimated 81-98% of hip and wrist fractures annually attributed to falls (Hedlund et al 1987; Parkkari et al. 1999). Surgical interventions and post-surgical management of fractures incur a huge cost to patients and to the health care system (Ray et al. 1995). Thus, reducing falls is very essential in improving upon the lives of individuals with higher fall risk as in stroke.

## 1.2 Perturbation training improves compensatory stepping response

External postural perturbation, such as a trip or slip, is one of the contributors to the high fall rate in individuals with stroke(Forster et al. 1995). A critical response to postural perturbation is the ability to perform a compensatory step. This is a recovery step used to restore balance and prevent a fall. (Maki et al. 2003; Mansfield et al. 2013). However, individuals with stroke are often unable to perform a compensatory step due to reduced trunk stability, shorter step length (Weerdesteyn et al. 2008), delayed step initiation (Davenport R.J. et al. 1996) , and the inability to initiate a stepping response with the paretic leg. One way to increase the ability to perform a compensatory step is by administering treadmill perturbation training to high-risk individuals (Bhatt et al. 2006; Mansfield et al. 2010; Peterson et al. 2016) . Individuals are subjected to several repetitions of forward-directed perturbation during standing or walking, which mimics a real-life event such as slipping on ice or backward-directed perturbation which mimics a trip. These perturbation trainings improve reactive balance and reduces fall risk in several population types by fortifying an individual's neuromuscular protective mechanism which affects the causal relationship between reduction of balance loss and improvement of stability (Mansfield et al. 2010).

### 1.3 Foot drop and gait deficits are improved by AFO/FES

Between 20% - 30% of individuals with stroke also have a motor deficit called foot drop, further increasing fall risk (Hartholt et al. 2011). In these cases, individuals have inadequate dorsiflexion required to clear their foot from the ground during the swing phase of gait, causing the individual to stumble and fall (Pouwels et al. 2009; Hartholt et al. 2011). To address both foot drop and poor compensatory stepping response following a slip/trip, assistive devices such as the ankle-foot-orthoses (AFO) and functional electrical stimulators (FES) are generally prescribed to stroke survivors. Thermoplastic AFOs are the most prescribed; these restrict ankle movement thereby preventing foot drop or plantarflexion (Kluding et al. 2013;  S. Whiteside et al. 2015). FES devices prevent foot drop by assisting dorsiflexion through the stimulation of the peroneal nerve during the swing phase of gait (Kluding et al. 2013).

## 1.4 AFO/FES users fall more

It is well established that AFO and FES devices enhance walking speed (Bethoux et al. 2014; Kluding et al. 2013; Tyson and Thornton 2001; Abe et al. 2009; Doğan et al. 2011; Franceschini et al. 2003; Everaert et al. 2013), foot clearance (Pongpipatpaiboon et al. 2018; Alam et al. 2014;  Everaert et al. 2013) , step length (Abe et al. 2009) , and cadence (Tyson and Thornton 2001; Alam et al. 2014). Despite this, their impact on fall outcomes in individuals with stroke is not well evaluated (Weerdesteyn et al. 2008). Short term studies indicate that FES devices reduce fall rate in stroke survivors by 92% during two months after prescription (Hausdorff and Ring 2008). On the other hand, a long-term study showed a high falling rate of 40% among stroke survivors 12 months after prescription (Bethoux, et al. 2015). A study by Nikamp et al also indicates that prescription timepoint affects the success in fall reduction rates. According to the study, early prescription of AFO to individuals with acute stroke was associated with 2.75 times more falls compared to the individual who prescribed an AFO with an 8-week delay (Nikamp et al. 2019).

A recent study (Masood Nevisipour et al. 2019) evaluating the impact of AFO and FES in eliciting a compensatory step subjected AFO and FES users with chronic stroke to forward treadmill perturbation. The results indicated that long term AFO/FES users fall *more often* than Non-users following trip-like perturbation, even though both groups had similar balance and mobility scores. However, the impaired compensatory stepping response of AFO/FES users is likely not related to the inhibitory mechanical effect of these assistive devices but to severe ankle impairments that AFO and FES do not fully address. It was suggested that future designs of these assistive devices should address these neurological impairments that prevent maximum plantarflexion, which is important for paretic step propulsion and whole-body angular momentum control. However, to our knowledge, no study has yet evaluated the impact of AFO and FES in eliciting a compensatory step during backward, slip-like perturbations.

### 1.5 Falls resulting from backward perturbations

Slips constitute 40% of outdoor falls among community-dwelling adults who are 70 years of age or older (Luukinen et al. 2000). Preventing slip related falls involves taking an effective recovery step. This does not only restore stability by rebuilding the base of support but could also provide extra limb support to retard hip descent, therefore decreasing fall risk and slip severity (Bhatt et al. 2005). Plantar flexor weakness and spasticity reduces paretic step propulsion (Weerdesteyn et al. 2008) and negatively impacts control of the body (Vistamehr et al. 2014; Neptune and McGowan 2011). This makes it difficult for AFO and FES users to elicit a compensatory step following an external perturbation which results in a fall.

## 1.6 Objectives and hypotheses

To comprehensively inform the design of future assistive devices in enhancing compensatory stepping response, it is very important to evaluate the mechanics of a compensatory step during a slip. The objective of the present study aims to quantify the fall rate between AFO and FES users and Non-users with chronic stroke when subjected to backward treadmill perturbation and to access the impact of AFO and FES on the mechanics of compensatory stepping response during a slip.

Since AFO and FES do not enhance compensatory stepping response following a forward perturbation, the hypotheses for this study was that AFO and FES will not enhance compensatory stepping response in backward perturbation as well. Also, AFO and FES users would fall more often than Non-users and have impaired compensatory stepping response compared to Non-users during backward perturbation.

# CHAPTER 2

# METHODOLOGY

## 2.1 Experimental setup

Thirty-nine individuals with unilateral chronic stroke (17 Non-users, 12 AFO users and 10 FES users) with the following eligibility criteria: ability to walk 5 minutes without assistance, no spinal/lower extremity injury/surgery in the past year, no history of fainting in the past year and at least a month of AFO/FES use daily participated in this study. Data was already collected in a previous study (Masood Nevisipour et al. 2019). This study focused on statistical analysis of a subset (39) of the total subjects recruited (42) during the data collection. However, the procedure for the data collection and analysis is outlined in this section.

All subjects provided written informed consent. The Non-users served as the control group for the study. Height and weight measurements were recorded for all subjects. Subjects were fitted into a safety received treadmill balance perturbations. Previous study that recruited 42 subjects of which 39 was involved in this study reported no difference in 10 meter walk test between the users in their natural condition (AFO/FES users wearing the device and Non-users without the device) (Masood Nevisipour et al. 2019).

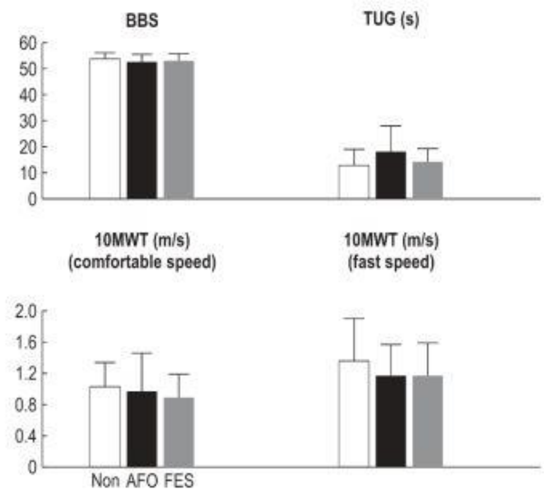


Figure 2.1: Comparison of clinical scores between the groups tested in their natural conditions (AFO and FES users with and Non-users without assistive devices respectively.) The figure represents the results obtained for the 42 recruited subjects (Masood Nevisipour et al 2019) of which 39 was included in the current analysis.

Perturbations were delivered in a fashion that required subjects to take a single or a multiple step to prevent falling. A fall is defined as when a subject is unambiguously caught by the safety harness. Posteriorly and anteriorly directed perturbations mimicking a trip and a slip respectively were delivered while subjects stood quiet on the treadmill. Thus, treadmill perturbations involved the eliciting of a forward or backward step to ensure recovery. This study focused on anteriorly directed perturbations with posteriorly directed perturbations delivered randomly to prevent subjects from predicting direction of movement. Treadmill perturbation was delivered under two conditions for all users; Condition 1: With the AFO/FES; Condition 2: Without the AFO/FES. Non-users wore a prefabricated semi-rigid AFO device during the first condition. Conditions were randomized for all subjects.

Figure 2.2: Prefabricated AFO device used for the experiment

Subjects were asked to walk on a dual-belt treadmill (GRAIL, Motek Medical BV, Amsterdam, The Netherlands) at their self-selected comfortable speed for a duration of two minutes to get acclimatized to each condition before the onset of the treadmill perturbation. Before delivering any treadmill perturbation, subjects were instructed to stand upright at their self-selected comfortable stance width, look straight ahead and try to do what is necessary (including taking steps) to regain balance and not fall as the treadmill moves in some direction at some time during the next 20 seconds." Anterior perturbations were delivered at two intensity levels (Level 1: small, Level 2: medium). Level 1 was designed such that subjects could recover with a single step whereas level 2 required at least 2 steps to recover. Perturbations had a trapezoid velocity profile similar to previously published studies in older adults (Crenshaw et al. 2014) and individuals with stroke (Nevisipour et al. 2019; Honeycutt et al. 2016). Displacement, constant velocity, acceleration, and deceleration of the anterior perturbations were as follows: small: 10% of body height(m), -0.9m/s, -0.9m/s$^2$, medium: 20% of body height(m), -1.1m/s, -11.0m/s$^2$, 11.0m/s$^2$. Posteriorly directed perturbations, delivered at three intensities (small, medium and large) to prevent direction anticipation had the following displacement, constant velocity, acceleration and deceleration values: small:17% of body height(m), 1.00m/s, 10.0m/s$^2$, -10.0m/s$^2$; medium: 32% of body height(m), 1.26m/s, 12.6m/s$^2$, -12.6m/s$^2$; and large: 47.5% of body height(m), 1.26m/s, 12.6m/s$^2$, -12.6m/s$^2$. At each condition, subjects received an initial round of two anteriorly and three posteriorly directed perturbations randomized in direction but in an increasing order of intensity. An additional two rounds of the same perturbations were delivered in a complete randomized fashion. However, if the subject fell on a perturbation level during the initial round, same perturbation was repeated up to three times and if the subject fell on all three trials, no more perturbation of that level or larger was delivered throughout the condition (i.e., that level and larger ones were removed from the second and third rounds with the assumption that the subject will record a complete fall at the higher perturbation level). Passive reflective markers were attached to the subject's body according to the modified Helen Hayes marker set (Kadaba et al. 1990). A 10-camera motion capture system (Vicon, Oxford, UK) was used to record markers trajectory data with a sampling rate of 250Hz. A $4_{th}$ order Butterworth filter with a 6Hz cut-off frequency was applied to the markers kinematic data using Vicon Nexus 2.6.1 (Vicon, Oxford, UK). Calculation of kinematic variables during the first compensatory step involved using filtered markers data and MATLAB software (Mathworks, Natick, MA). The following kinematic variables were calculated to evaluate the effectiveness of the first compensatory step: Trunk flexion and velocity, step length (normalized to body height), COM-BOS (normalized to body height), COM-BOS velocity (normalized to body height), reaction time and step duration. The inability to elicit a second step when required to prevent a fall was calculated as well (second step failure). Trunk flexion and velocity were calculated at the initiation (SS: Step Start) and completion (SE: Step End) of the first compensatory step. A step is defined as when the subject lifts the foot off the treadmill after perturbation onset (SS) and places it down (SE) with the heel of the stepping foot seen posterior to the heel of the slipping foot. SS and SE were detected using the ground reaction force (GRF) of the stepping leg with a 20N threshold.

Table 2.1: Definition of kinematic variables

| **Dependent variables** | **Definition** |
|---|---|
| Trunk flexion | The angle between the trunk and vertical line in the sagittal plane relative to the initial angle of the trunk at perturbation onset. Posterior trunk inclination is considered negative direction. |
| Trunk flexion velocity | First derivative of trunk flexion with respect to time. |
| Step length | The anterior -posterior displacement between stepping and support foot centers at SE. |
| COM-BOS (Dx) | The anterior-posterior displacement between the center of mass (COM) and the boundary of base of support (BOS) (i.e., stepping leg heel marker) at SE. Negative values represent COM within (i.e., posterior to) the base of support. |
| COM-BOS velocity | First derivative of the center of mass (COM) and the boundary of base of support (BOS) with respect to time.<br>This defines the relative velocity between the center of mass and the base of support. |
| Reaction time | The time from perturbation onset to toe-off (i.e., SS). |
| Step duration | The time from step initiation (SS) to step completion (SE). |
| Second step failure rate | Percentage of times that subject is required to take a second step but fails to do that. A second step is often required in any trial except the ones that subject recovers from the perturbation with a single step.<br>A second step is counted only when the foot is lifted from the treadmill (verified by GRFs) and lands fully or partially posterior to the other foot (this was manually verified by observing the anterior-posterior position of the heel markers by the experimenter).<br>A second step failure is recorded when a subject fails to initiate or complete a second step and falls or uses the same leg to take the step (i.e. pivot/hopping) (Honeycutt et al. 2016). |

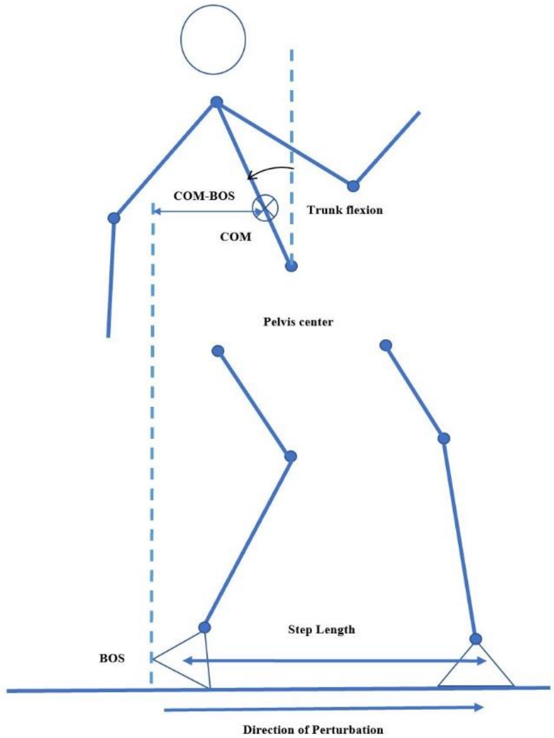


Figure 2.3: Subject's body configuration at the completion of first compensatory step with kinematic variables indicated. All variables are depicted in the negative direction/orientation.

## 2.2 Fall rate calculation

Fall rate at each perturbation level was calculated as the ratio of the number of falls to the total number of perturbations delivered on that level. At each condition, 3 rounds of each perturbation level were delivered unless the subject fell three times on a specific perturbation. When this happens, the subject does not receive perturbations of greater intensity. The fall rate on the greater perturbation levels is therefore assumed to be 100%. Since the study focused on anteriorly directed perturbation that mimics a slip, fall rate calculation for the second perturbation level involved two different calculations. Fall rate results when the assumed values were not recorded during the statistical analysis (i.e., level 2 NR) and fall rate results when the assumed values were recorded (i.e., level 2 R) and included in the statistical analysis. This involved 6 AFO users, 4 FES users and 4 Non-users who had a 100% fall rate on the first perturbation level. Total fall rate and fall rate at each level were compared between AFO users, FES users, and Non-users at their natural condition (i.e., AFO and FES users wearing their orthosis/device and Non-users not wearing any AFOs) and for AFO and FES users with and without the use of their device.

### 2.3 Statistical analysis

A general linear mixed effect model using R (R Development Core Team, 2006) was performed. The three different groups (AFO user, FES user, Non-user), two conditions (with and without the use of the assistive device) and two levels (1,2) were treated as independent variables and fall rate at each perturbation level as the dependent variable. Subjects were treated as random factors. Statistical significance was defined as when p-value $< 0.05$. Kinematic variables were also treated as dependent variables and compared between users at their natural conditions. Tukey HSD was used for all post-hoc comparisons. All p-values obtained in this study reflected interaction effects. The mean of all the data points for each subject was calculated and the final mean value was obtained by averaging all the mean values for all subjects under a specific condition. This was applied for fall rate, kinematic variables analyzed and the second step failure as well.

# CHAPTER 3

# RESULTS

## 3.1 Fall rate results

AFO user's total fall rate was 1.6 times more than that of Non-users at the two perturbation levels combined (i.e., levels 1 and 2) when the groups were compared in their natural conditions (AFO users wearing their device = 72.22 ± 31.2%, Non-users without wearing any assistive device = 43.87 ± 42.24, P value = 0.023). However, no significant difference in total fall rate was recorded at the two perturbation levels between FES users and Non-users in their natural conditions between (P value = 0.2088). No differences in total fall rate were found amongst the three groups at the individual perturbation levels (P value > 0.05).

No differences in fall rate were found between the groups at both the recorded (level 2 R) and not-recorded (level 2 NR) fall values between the two groups (P value > 0.05). AFO and FES users showed no difference in fall rate for the two conditions (with and without using the assistive device) at the individual perturbation levels (P value > 0.05).

### 3.1.1 Fall rate for AFO and FES users

Table 3.1: Fall rate for AFO and FES at level 1

| Fall Rate | | | |
|---|---|---|---|
| Level 1 | | | |
| **Group (Condition)** | | **Mean ± S.D** | **P-Value** |
| AFO (W&WO) | W | 52.78 ± 45.97 | 0.657 |
| | WO | 56.67 ± 50.33 | |
| FES (W&WO) | W | 58.99 ± 42.10 | 0.7362 |
| | WO | 51.85 ± 43.66 | |

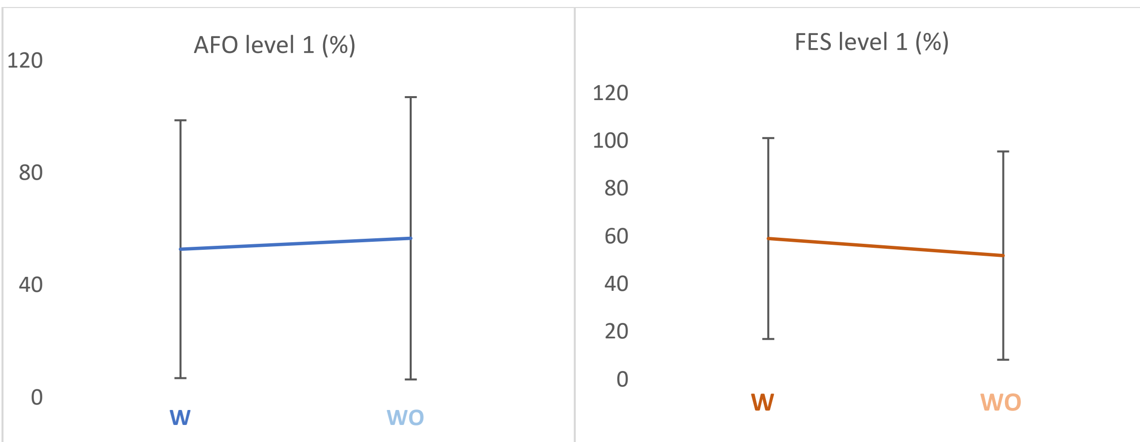


Figure 3.1: Fall rate comparison of AFO and FES users at level 1 with(W) and without (WO) the use of the assistive device.
Analysis for AFO: Involved 21 and 22 data points obtained for 12 subjects with (W) and without (WO) the use of the device.
Analysis for FES: Involved 42 data points obtained for 10 subjects with (W) and 33 data points obtained for 9 subjects without (WO) using the device.

Table 3.2: Fall rate for AFO and FES at level 2

| Fall Rate | | | |
|---|---|---|---|
| Level 2 (NR) | | | |
| **Group (Condition)** | | **Mean ± S.D** | **P-Value** |
| AFO (W&WO) | W | 85.71 ± 37.7 | 0.91 |
| | WO | 83.33 ± 40.82 | |
| FES (W&WO) | W | 83.33 ± 40.82 | 1 |
| | WO | 83.33 ± 40.82 | |

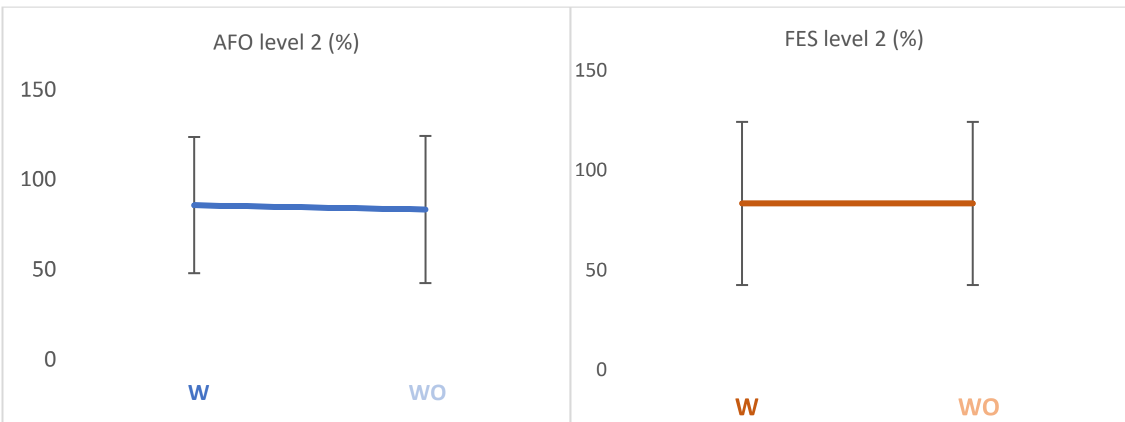


Figure 3.2: Fall rate comparison of AFO and FES users at level 2 with(W) and without (WO) the use of the assistive device.
Analysis for AFO: Involved 16 data points obtained for 7 subjects with (W) and 14 data points obtained for 5 subjects without (WO) using the device.
Analysis for FES: Involved 19 and 13 data points obtained for 6 subjects with (W) and without (WO) using the device.

Table 3.3: Fall rate for AFO and FES at level 2

| **Fall Rate** | | | |
|---|---|---|---|
| **Level 2 (R)** | | | |
| **Group (Condition)** | | **Mean ± S.D** | **P-Value** |
| AFO (W&WO) | W | 91.66 ± 28.87 | 0.95 |
| | WO | 90.91 ± 30.15 | |
| FES (W&WO) | W | 90.33 ± 31.62 | 1 |
| | WO | 88.89 ± 33.33 | |

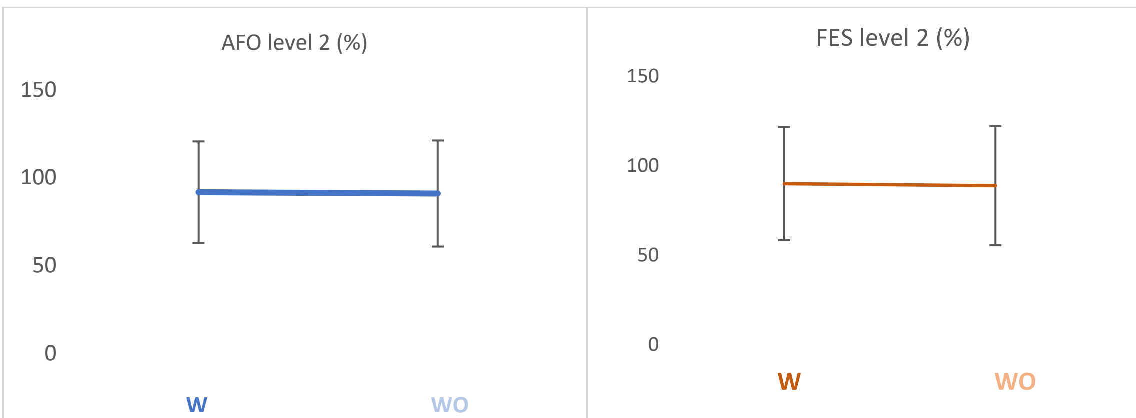


Figure 3.3: Fall rate comparison of AFO and FES users at level 2 with(W) and without (WO) the use of the assistive device.
Values included were assumed fall rate values due to complete fall recorded in level 1. No additional data points can be added since the actual trials were not given to subjects.

Table 3.4: Total fall rate for AFO and FES at levels 1 and 2

| **Total Fall Rate** | | | |
|---|---|---|---|
| **Levels 1&2** | | | |
| **Group (Condition)** | | **Mean ± S.D** | **P-Value** |
| AFO (W&WO) | W | 72.22 ± 31.25 | 0.3524 |
| | WO | 77.5 ± 24.91 | |
| FES (W&WO) | W | 74.50 ± 31.95 | 0.8042 |
| | WO | 70.37 ± 32.84 | |

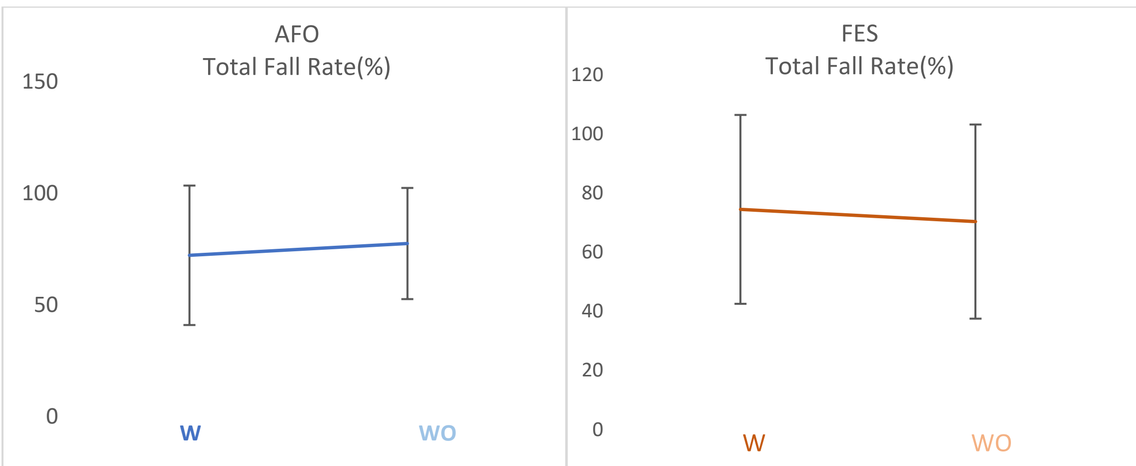


Figure 3.4: Total fall rate comparison of AFO and FES users at level 1 with(W) and without (WO) the use of the assistive device.
Analysis for AFO: Involved 37 and 36 data points obtained for 12 subjects with (W) and without (WO) using the device.
Analysis for FES: Involved 61 data points obtained for 10 subjects with (W) and 46 data points obtained for 9 subjects without (WO) using the device.

### 3.1.2 Total fall rate for AFO, FES and Non-users in their natural conditions

Table 3.5: Total fall rate for all users at level 1

| Total Fall Rate | | | |
|---|---|---|---|
| Level 1 | | | |
| **Group (Condition)** | **Mean ± S.D** | | **P-Value** |
| AFO (W) | 52.78 ± 45.97 | AFO-NON | 0.247 |
| FES (W) | 58.99 ± 42.10 | AFO-FES | 0.7112 |
| NON(WO) | 29.16 ± 46.97 | FES-NON | 0.1329 |

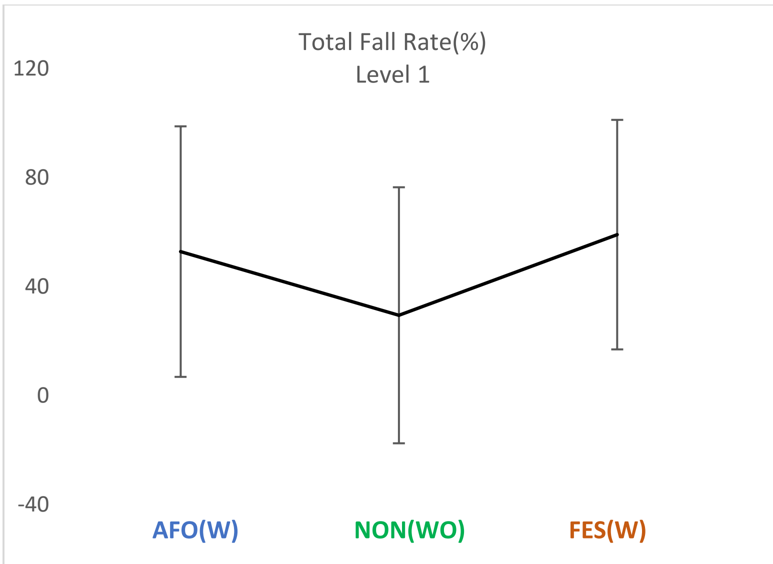


Figure 3.5: Total fall rate comparison of all users at level 1 in their natural condition. (i.e., AFO and FES with(W) and Non-users without (WO) their assistive device. Analysis involved 21 data points obtained for 12 AFO users, 52 data points obtained for 17 Non-users and 42 data points obtained for 10 FES users.

Table 3.6: Total fall rate for all users at level 2

| **Total Fall Rate** | | | |
|---|---|---|---|
| **Level 2 (NR)** | | | |
| **Group (Condition)** | **Mean ± S.D** | | **P-Value** |
| AFO (W) | 72.22 ± 31.2 | AFO-NON | 0.0782 |
| FES (W) | 74.50 ± 31.95 | FES-NON | 0.101 |
| NON(WO) | 43.87 ± 42.24 | | |

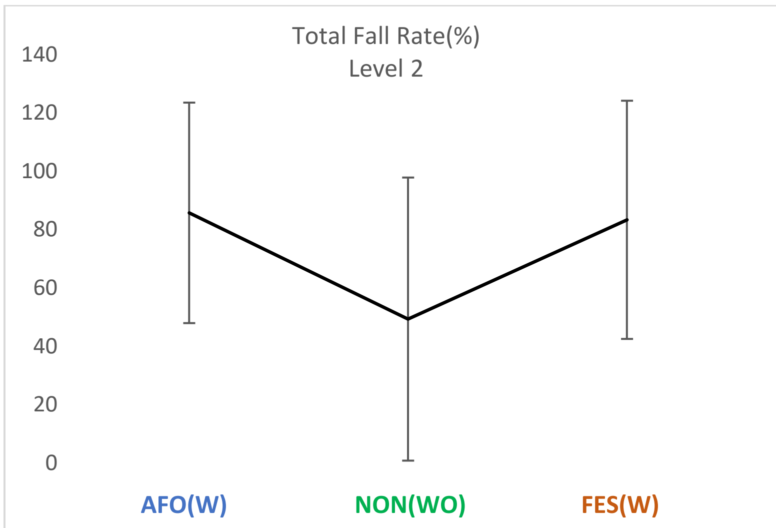


Figure 3.6: Total fall rate comparison of all users at level 2 in their natural condition. (i.e., AFO and FES with(W) and Non-users without (WO) their assistive device. Analysis involved 16 data points obtained for 7 AFO users, 35 data points obtained for 12 Non-users and 19 data points obtained for 6 FES users.

Table 3.7: Total fall rate for all users at level 2

| Total Fall Rate | | | |
|---|---|---|---|
| **Level 2 (R)** | | | |
| **Group (Condition)** | **Mean ± S.D** | | **P-Value** |
| AFO (W) | 91.67 ± 28.87 | AFO-NON | 0.0737 |
| FES (W) | 90 ± 31.62 | AFO-FES | 1 |
| NON(WO) | 61.97 ± 47.33 | FES-NON | 0.0853 |

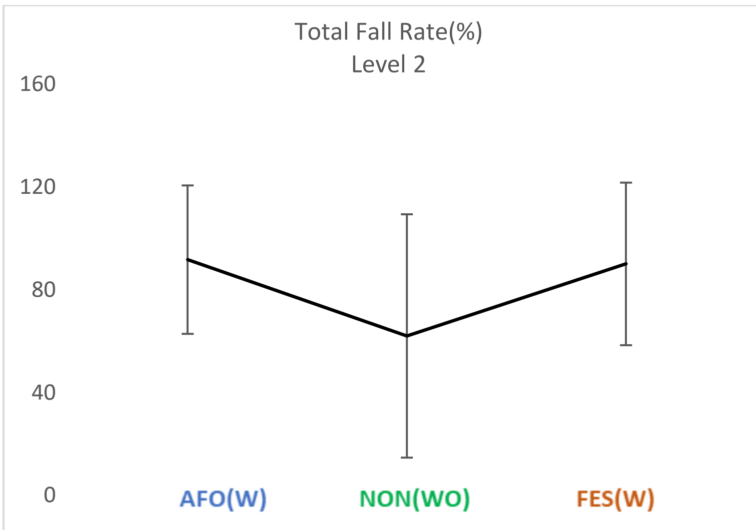


Figure 3.7: Total fall rate comparison of all users at level 2 in their natural condition. (i.e., AFO and FES with(W) and Non-users without (WO) their assistive device. Values included were assumed fall rate values due to complete fall recorded in level 1. No additional data points can be added since the actual trials were not given to subjects.

Table 3.8: Total fall rate for all users at level 2

| Total Fall Rate | | | |
|---|---|---|---|
| Levels 1&2 | | | |
| **Group (Condition)** | **Mean ± S.D** | | **P-Value** |
| AFO (W) | 72.22 ± 31.2 | AFO-NON | 0.0213 |
| FES (W) | 74.50 ± 31.95 | AFO-FES | 0.7522 |
| NON(WO) | 43.87 ± 42.24 | FES-NON | 0.2088 |

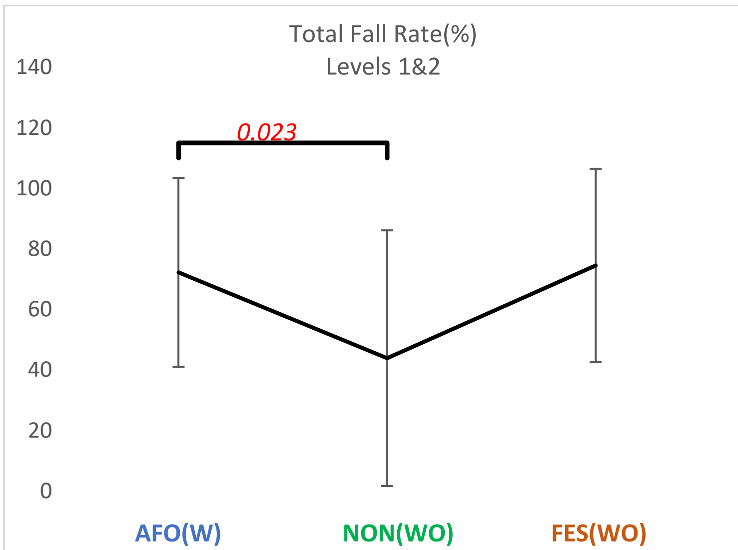


Figure 3.8: Total fall rate comparison of all users at both levels in their natural condition. (i.e., AFO and FES with(W) and Non-users without (WO) their assistive device. Analysis involved 37 data points obtained for 12 AFO users, 87 data points obtained for 17 Non-users and 61 data points obtained for 10 FES users.

### 3.1 Kinematic results

FES users showed an increase in step duration at level 2 when compared with Non-users in their natural conditions (FES users with assistive device = 173.67 ± 37.63, Non-users without assistive device = 138.47 ± 19.81, P-value = 0.0339). However, no differences were recorded in any other kinematic variable between FES and AFO users compared with Non-users respectively at any of the two perturbation levels (P-value > 0.05). No differences were found in any of the kinematic variables analyzed in both AFO and FES users between the two conditions (with and without the use of their assistive devices) at the individual perturbation levels (P-value > 0.05).

### 3.2.1 Kinematic results for AFO users

Table 3.9: Compensatory stepping response for AFO users at level 1. Abbreviations: W=with assistive device, WO=without assistive device, S.D -standard deviation

| **AFO KINEMATICS LEVEL 1** | | | | |
|---|---|---|---|---|
| **Kinematic variable (unit)** | | **Condition** | **Mean ± S.D** | **P-value** |
| Trunk flexion (deg) | Step Start | W | 0.46 ± 4.9 | 0.9956 |
| | | WO | 0.47 ± 3.5 | |
| | Step End | W | 1.23 ± 10.65 | 0.4614 |
| | | WO | 3.34 ± 8.09 | |
| Trunk flexion velocity (deg/s) | Step Start | W | 16.15 ± 54.06 | 0.5203 |
| | | WO | 25.31 ± 43.19 | |
| | Step End | W | -17.45 ± 50.34 | 0.119 |
| | | WO | 7.39 ± 53.63 | |
| COM-BOS (%bh) | | W | 9.43 ± 55.13 | 0.3466 |
| | | WO | 26.79 ± 82.90 | |
| COM-BOS velocity (%bh) | | W | -277.16 ± 287.80 | 0.4307 |
| | | WO | -208.50 ± 379.92 | |
| Step length (%bh) | | W | 74.25 ± 49.38 | 0.5716 |
| | | WO | 82.12 ± 44 76 | |
| Step duration (ms) | | W | 135.06 ± 47.47 | 0.9023 |
| | | WO | 136.08 ± 48.68 | |
| Reaction time (ms) | | W | 317.28 ± 141.96 | 0.0561 |
| | | WO | 296.1 ± 126.36 | |
| Second step failure (%) | | W | 40.28 ±46.85 | 0.7949 |
| | | WO | 41.67 ± 51.49 | |

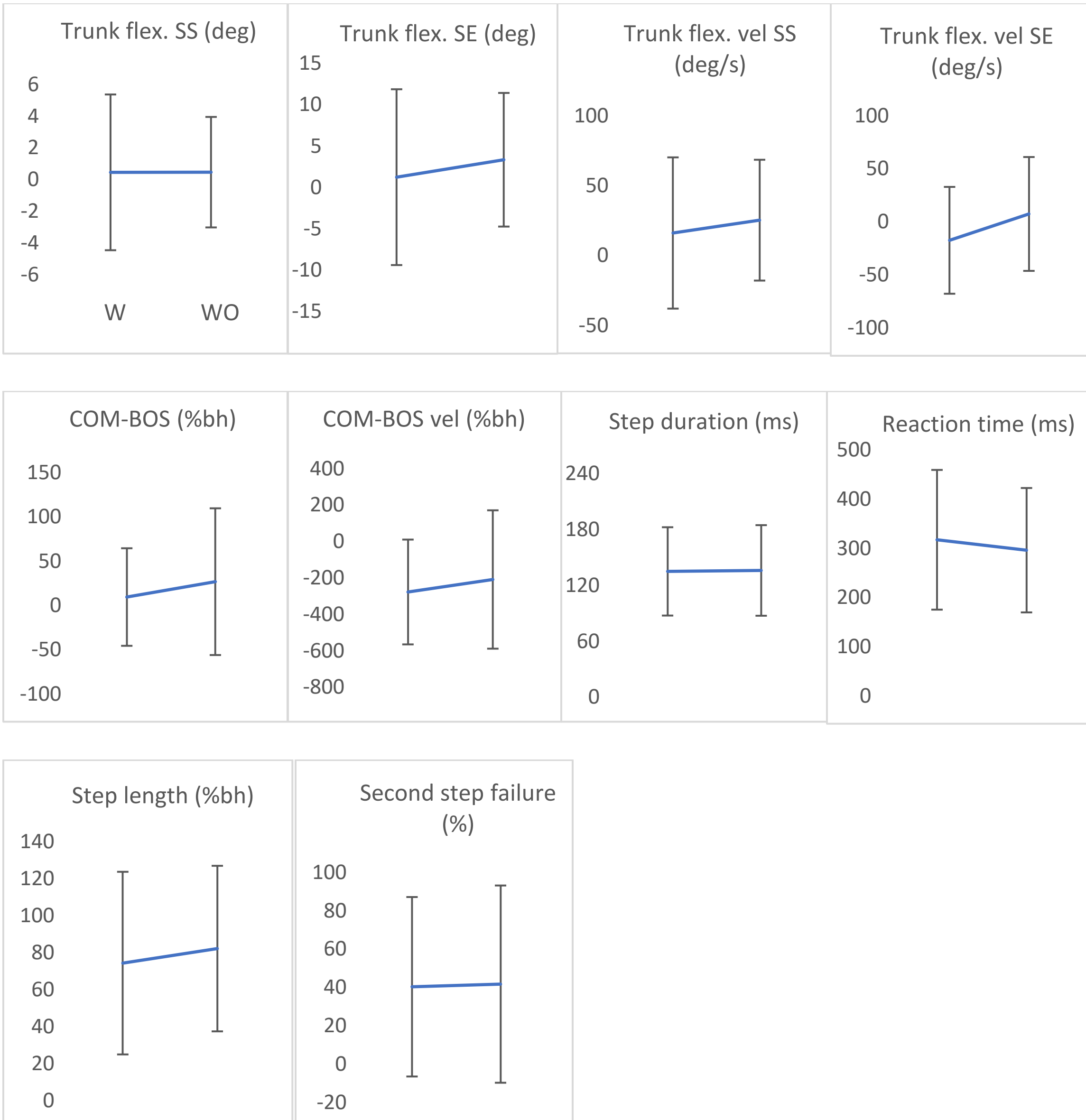


Figure 3.9: Comparison of compensatory stepping response of AFO users with(W) and without (WO) the use of their assistive device at level 1. Abbreviations: flex=flexion, vel=velocity. SS=step start, SE=step end, bh=body height, COM=center of mass, BOS=base of support.

Analysis involved 33 and 37 data points obtained for each kinematic variable under the conditions, with (W) and without (WO) the use of AFO respectively and 39 data points obtained for second step failure under each condition (W &WO) for 12 subjects.

Table 3.10: Compensatory stepping response for AFO users at level 2. Abbreviations: W=with assistive device, WO=without assistive device, S.D -standard deviation

| **AFO KINEMATICS<br>LEVEL 2** | | | | |
|---|---|---|---|---|
| **Kinematic variable (unit)** | | **Condition** | **Mean ± S.D** | **P-value** |
| Trunk flexion (deg) | Step Start | W | -2.32 ± 7.11 | 0.3974 |
| | | WO | 1.09 ± 4.11 | |
| | Step End | W | -3.33 ± 10.69 | 0.6582 |
| | | WO | -0.21 ± 10.39 | |
| Trunk flexion velocity (deg/s) | Step Start | W | 4.93 ± 42.99 | 0.9181 |
| | | WO | 2.51 ± 48.06 | |
| | Step End | W | 3.23 ± 59.35 | 0.7916 |
| | | WO | 0.82 ± 59.48 | |
| COM-BOS (%bh) | | W | 55.85 ± 70.18 | 0.7244 |
| | | WO | 74.79 ± 100.40 | |
| COM-BOS velocity (%bh) | | W | -144.57 ± 296.95 | 0.5083 |
| | | WO | -27.77 ± 245.69 | |
| Step length (%bh) | | W | 135.26 ± 47.49 | 0.378 |
| | | WO | 113.67 ± 59.18 | |
| Step duration (ms) | | W | 204.19 ± 96.67 | 0.1969 |
| | | WO | 136.13 ± 18.49 | |
| Reaction time (ms) | | W | 239.14 ± 131.93 | 0.9326 |
| | | WO | 244 ± 11.27 | |
| Second step failure (%) | | W | 23.80 ± 41.79 | 0.8897 |
| | | WO | 20 ± 44.72 | |

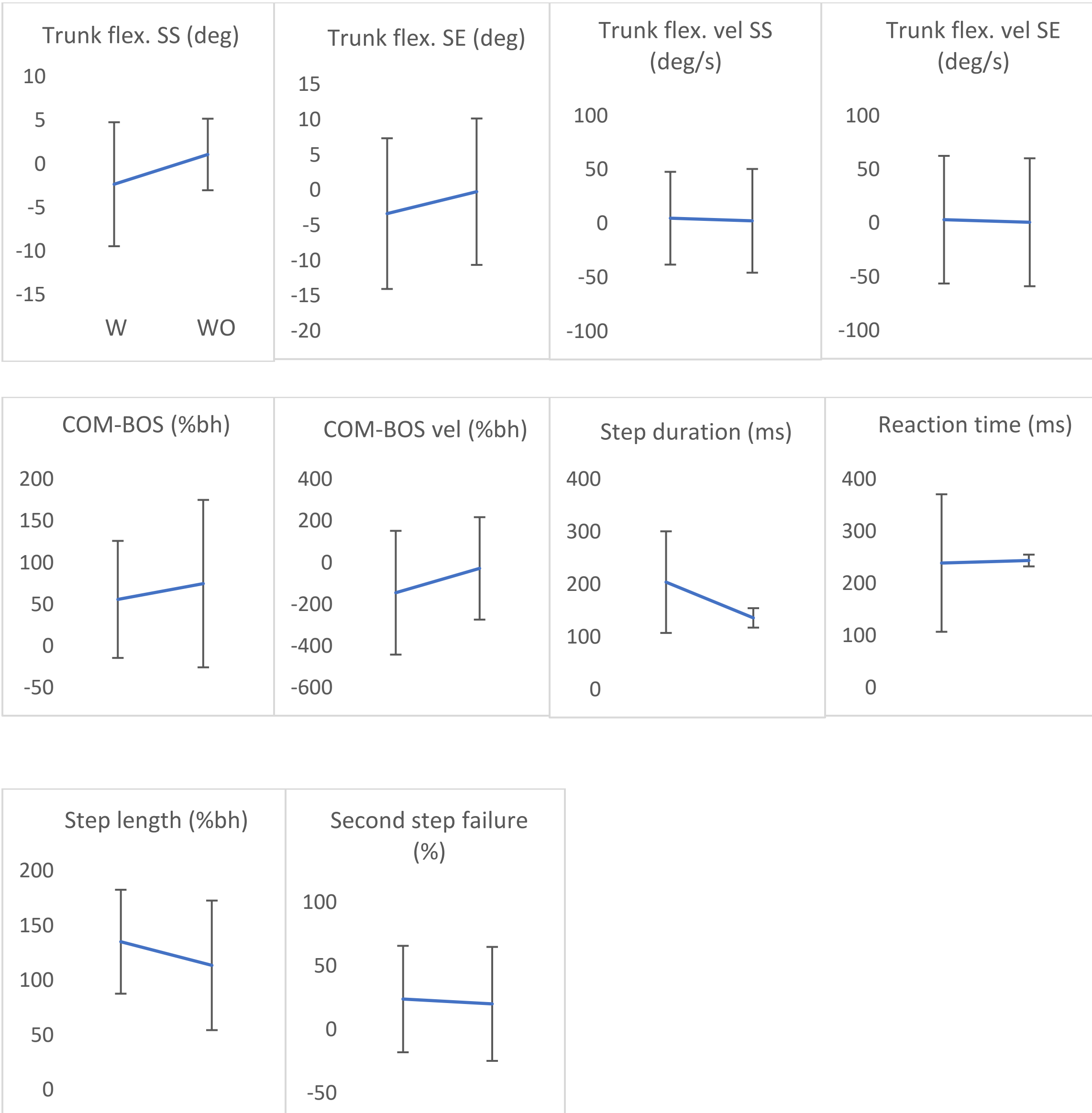


Figure 3.10: Comparison of compensatory stepping response of AFO users with(W) and without (WO) the use of their assistive device at level 2. Abbreviations: flex=flexion, vel=velocity. SS=step start, SE=step end, bh=body height, COM=center of mass, BOS=base of support.

Analysis involved 20 data points obtained for each kinematic variable and second step failure for 7 subjects with the use of AFO(W) and 14 data points obtained for each kinematic variable and second step failure for 5 subjects without the use of AFO(WO).

### 3.2.2 Kinematic results for FES users

Table 3.11: Compensatory stepping response for FES users at level 1. Abbreviations: W=with assistive device, WO=without assistive device, S.D -standard deviation

| FES KINEMATICS LEVEL 1 | | | | |
|---|---|---|---|---|
| **Kinematic variable (unit)** | | **Condition** | **Mean ± S.D** | **P-value** |
| Trunk flexion (deg) | Step Start | W | 2.70 ± 8.28 | 0.9726 |
| | | WO | 2.90 ± 8.47 | |
| | Step End | W | 0.03 ± 13.59 | 0.7938 |
| | | WO | -0.44 ± 12.28 | |
| Trunk flexion velocity (deg/s) | Step Start | W | 11.51 ± 48.06 | 0.4607 |
| | | WO | 4.65 ± 51.17 | |
| | Step End | W | 5.83 ± 41.39 | 0.4261 |
| | | WO | -10.53 ± 43.39 | |
| COM-BOS (%bh) | | W | 0.34 ± 93.47 | 0.9467 |
| | | WO | -0.46 ± 83.81 | |
| COM-BOS velocity (%bh) | | W | -273.78 ± 285.25 | 0.7979 |
| | | WO | -249.34 ± 234.91 | |
| Step length (%bh) | | W | 109.59 ± 74.21 | 0.4353 |
| | | WO | 127.68 ± 86.21 | |
| Step duration (ms) | | W | 159.84 ± 62.24 | 0.4811 |
| | | WO | 168.73 ± 48.57 | |
| Reaction time (ms) | | W | 324.4 ± 106.15 | 0.7073 |
| | | WO | 310.79 ± 84.61 | |
| Second step failure (%) | | W | 36 ± 40.27 | 0.3898 |
| | | WO | 22.22 ± 33.33 | |

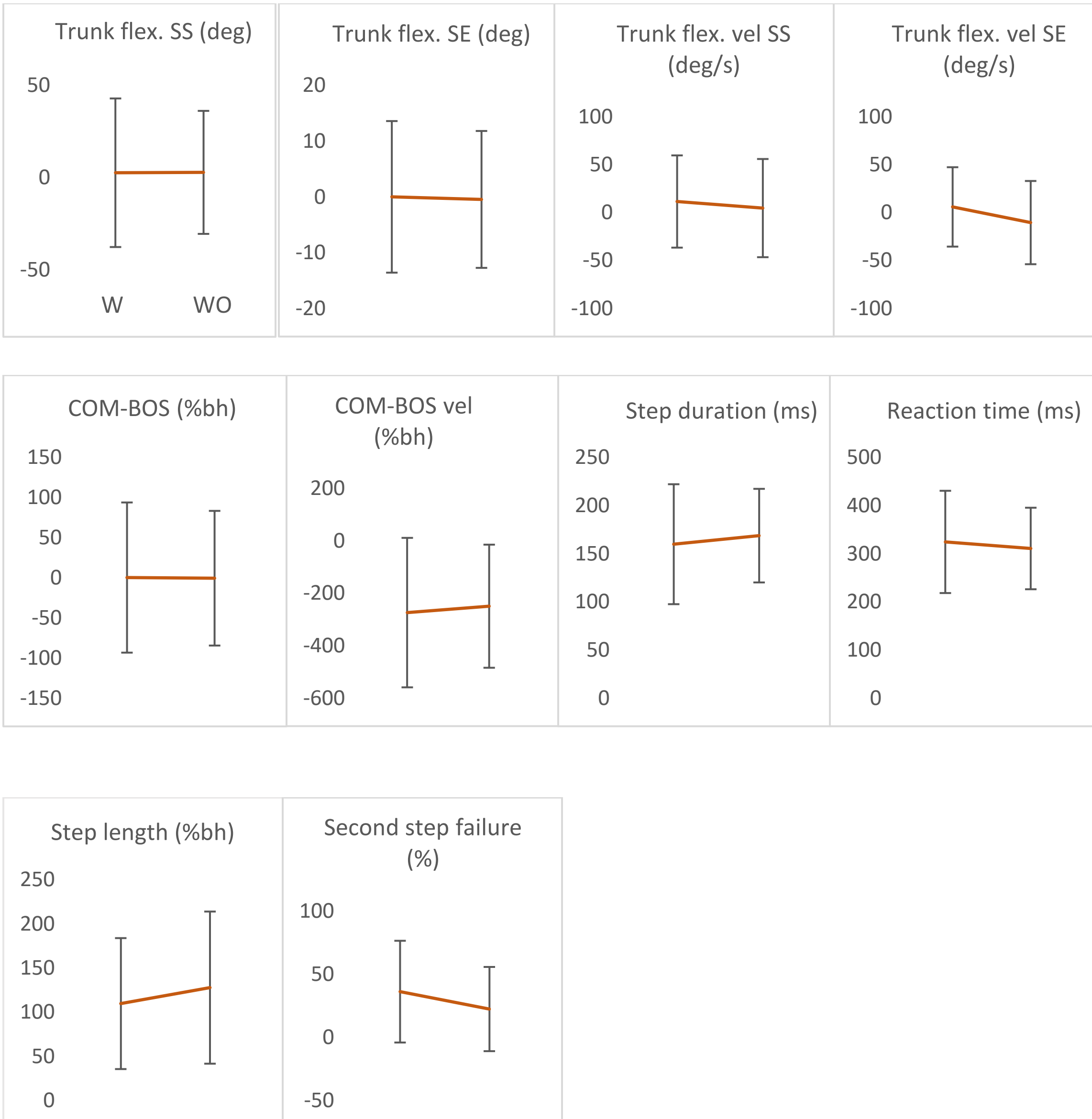


Figure 3.11: Comparison of compensatory stepping response of FES users with(W) and without (WO) the use of their assistive device at level 1. Abbreviations: flex=flexion, vel=velocity. SS=step start, SE=step end, bh=body height, COM=center of mass, BOS=base of support.

Analysis involved 39 and 40 data points obtained for each kinematic variable and second step failure respectively for 10 subjects with (W) the use of the device and 30 and 32 data points obtained for each kinematic variable and second step failure respectively for 9 subjects without (WO) the use of the device.

Table 3.12: Compensatory stepping response for FES users at level 2. Abbreviations: W=with assistive device, WO=without assistive device, S.D -standard deviation

| **FES KINEMATICS LEVEL 2** | | | | |
|---|---|---|---|---|
| **Kinematic variable (unit)** | | **Condition** | **Mean ± S.D** | **P-value** |
| Trunk flexion (deg) | Step Start | W | 3.69 ± 3.67 | 0.8278 |
| | | WO | 3.23 ± 5.15 | |
| | Step End | W | -0.84 ± 13.29 | 0.4504 |
| | | WO | -3.62 ± 12.45 | |
| Trunk flexion velocity (deg/s) | Step Start | W | 22.71 ± 45.42 | 0.9307 |
| | | WO | 21.61 ± 42,82 | |
| | Step End | W | -15.27 ± 64.38 | 0.2661 |
| | | WO | -35.70 ± 51.67 | |
| COM-BOS (%bh) | | W | 51.23 ± 79.76 | 0.8411 |
| | | WO | 55.02 ± 72.73 | |
| COM-BOS velocity (%bh) | | W | -365.12 ± 261.39 | 0.1477 |
| | | WO | -236.52 ± 342.47 | |
| Step length (%bh) | | W | 199.39 ± 52.91 | 0.2256 |
| | | WO | 176.71 ± 53.95 | |
| Step duration (ms) | | W | 173.67 ± 37.63 | 0.2207 |
| | | WO | 185.11 ± 54.57 | |
| Reaction time (ms) | | W | 328.39 ± 102.98 | 0.1235 |
| | | WO | 276.78 ± 70.06 | |
| Second step failure (%) | | W | 66.67 ± 51.64 | 0.3632 |
| | | WO | 47.22 ± 45.24 | |

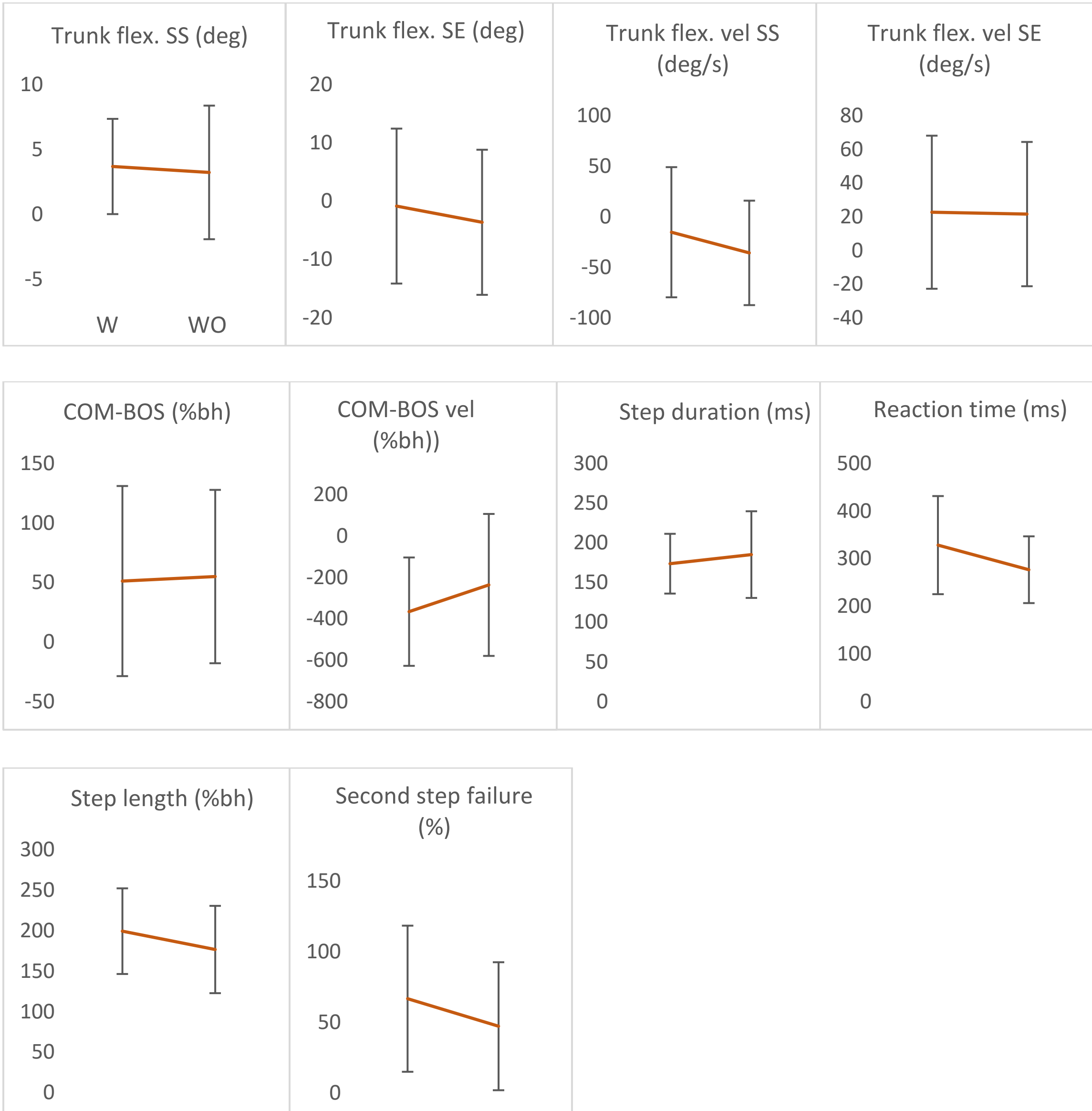


Figure 3.12: Comparison of compensatory stepping response of FES users with(W) and without (WO) the use of their assistive device at level 2. Abbreviations: flex=flexion, vel=velocity. SS=step start, SE=step end, bh=body height, COM=center of mass, BOS=base of support.

Analysis involved 19 and 15 data points obtained for each kinematic variable and second step failure for 6 subjects under the conditions with (W) and without (WO) the use of the device, respectively.

### 3.2.3 Kinematic results for AFO, FES and Non-users in their natural conditions

Table 3.13: Compensatory stepping response for AFO, FES and Non-users in their natural condition at level 1 (i.e., AFO and FES users wearing their orthosis/device(W) and Non-users without any AFO(WO))

| **KINEMATICS (Natural Condition) LEVEL 1** | | | | | |
|---|---|---|---|---|---|
| **Kinematic variable(unit)** | | **Condition** | **Mean ± S.D** | | **P-Value** |
| Trunk flexion (deg) | Step Start | AFO(W) | 0.46 ± 4.91 | AFO-NON | 0.3787 |
| | | FES(W) | 2.7 ± 8.28 | FES-NON | 0.8444 |
| | | NON(WO) | 2.13 ± 6.06 | | |
| | Step End | AFO | 1.23 ± 10.65 | AFO-NON | 0.9743 |
| | | FES | 0.03 ± 13.59 | FES-NON | 0.8353 |
| | | NON | 1.06 ± 10.81 | | |
| Trunk flexion velocity (deg/s) | Step Start | AFO | 16.14 ± 54.06 | AFO-NON | 0.8097 |
| | | FES | 11.51 ± 48.06 | FES-NON | 0.6487 |
| | | NON | 20.14 ± 42.73 | | |
| | Step End | AFO | -17.45 ± 50.34 | AFO-NON | 0.162 |
| | | FES | 5.83 ± 41.39 | FES-NON | 0.7284 |
| | | NON | 9.38 ± 44.36 | | |
| COM-BOS (%bh) | | AFO | 9.43 ± 55.13 | AFO-NON | 0.432 |
| | | FES | 0.34 ± 93.47 | FES-NON | 0.3638 |
| | | NON | 33.38 ± 81.37 | | |
| COM-BOS velocity (%bh) | | AFO | -277.16 ± 287.80 | AFO-NON | 0.2091 |
| | | FES | -273.78 ± 285.25 | FES-NON | 0.25 |
| | | NON | -118.28 ± 328.37 | | |
| Step length (%bh) | | AFO | 74.25 ± 49.38 | AFO-NON | 0.4772 |
| | | FES | 109.59 ± 74.21 | FES-NON | 0.4548 |
| | | NON | 88.91 ± 57.71 | | |
| Step duration (ms) | | AFO | 135.06 ± 47.47 | AFO-NON | 0.3272 |
| | | FES | 159.84 ± 62.24 | FES-NON | 0.378 |
| | | NON | 130.23 ± 68.11 | | |
| Reaction time (ms) | | AFO | 317.28 ± 141.96 | AFO-NON | 0.3803 |
| | | FES | 324.4 ± 106.15 | FES-NON | 0.2104 |
| | | NON | 278.27 ± 81.82 | | |
| Second step failure (%) | | AFO | 40.28 ± 46.85 | AFO-NON | 0.0648 |
| | | FES | 36 ± 40.27 | FES-NON | 0.1494 |
| | | NON | 14.61 ± 30.32 | | |

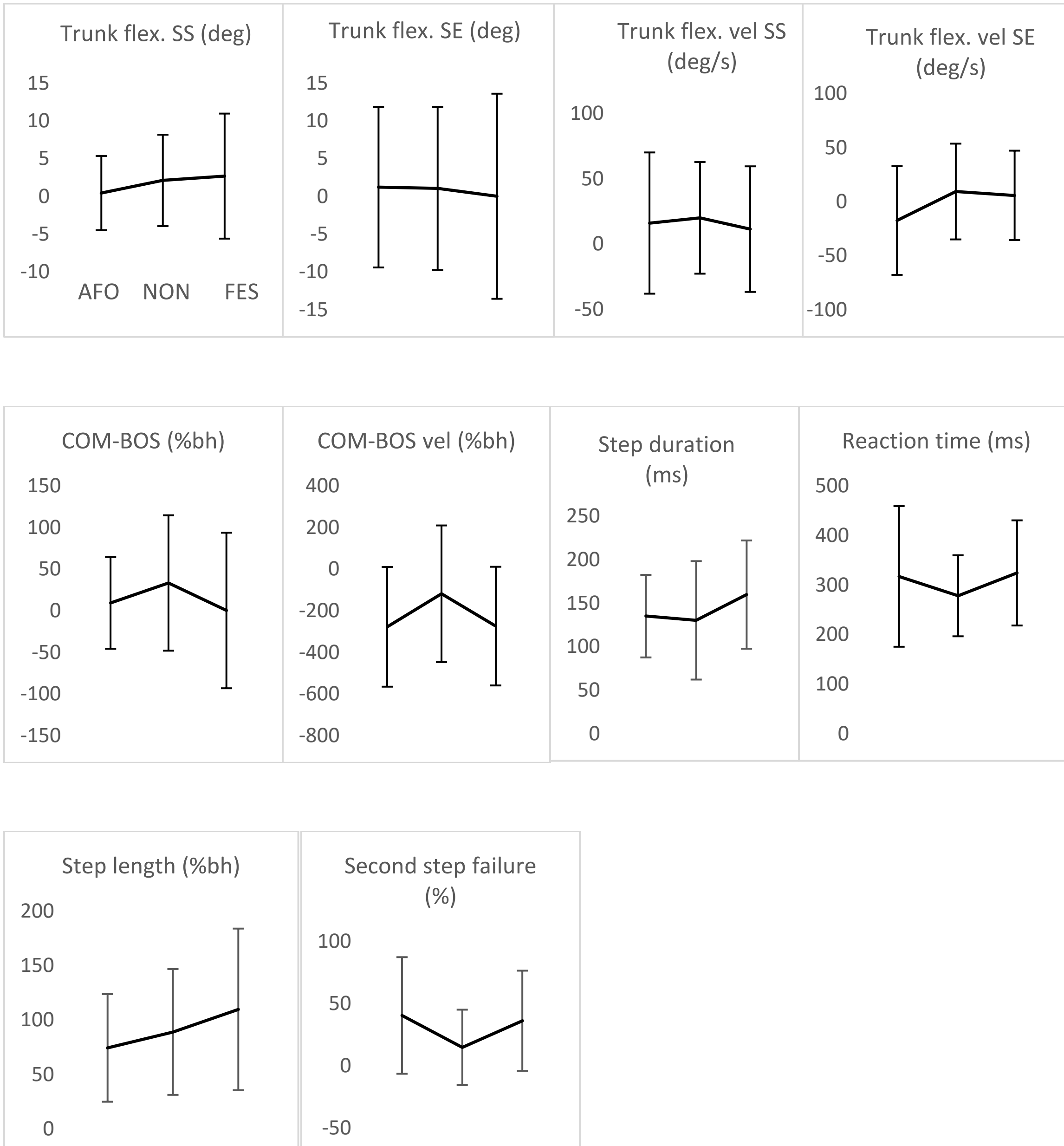


Figure 3.13: Comparison of compensatory stepping response of all users tested in their natural conditions at level 1 (i.e., AFO and FES users wearing their orthosis(W) and Non-users without any AFO(WO)). Abbreviations: flex=flexion, vel=velocity. SS=step start, SE=step end, bh=body height, COM=center of mass, BOS=base of support.
Analysis involved 33 data points for 12 AFO subjects, 39 data points for 10 FES subjects and 51 data points for 17 Non-users.

Table 3.14: Compensatory stepping response for AFO, FES and Non-users in their natural condition at level 2 (i.e., AFO and FES users wearing their orthosis/device(W) and Non-users without any AFO(WO))

| **KINEMATICS (Natural Condition) LEVEL 2** | | | | | |
|---|---|---|---|---|---|
| **Kinematic variable(unit)** | | **Condition** | **Mean ± S.D** | | **P-Value** |
| Trunk flex (deg) | Step Start | AFO(W) | -2.32 ± 7.11 | AFO-NON | 0.4429 |
| | | FES(W) | 3.69 ± 3.67 | FES-NON | 0.0651 |
| | | NON(WO) | -0.3 ± 3.55 | | |
| | Step End | AFO | -3.33 ± 10.69 | AFO-NON | 0.6344 |
| | | FES | -0.84 ± 13.29 | FES-NON | 0.3353 |
| | | NON | -6.31 ± 8.27 | | |
| Trunk flexion velocity (deg/s) | Step Start | AFO | 4.93 ± 42.99 | AFO-NON | 0.0642 |
| | | FES | 22.71 ± 45.42 | FES-NON | 0.1771 |
| | | NON | -8.52 ± 37.59 | | |
| | Step End | AFO | 3.23 ± 59.35 | AFO-NON | 0.2957 |
| | | FES | -15.27 ± 64.38 | FES-NON | 0.6207 |
| | | NON | -32.36 ± 61.99 | | |
| COM-BOS (%bh) | | AFO | 55.85 ± 70.18 | AFO-NON | 0.5585 |
| | | FES | 51.23 ± 79.76 | FES-NON | 0.4804 |
| | | NON | 79.5 ± 82.97 | | |
| COM-BOS velocity (%bh) | | AFO | -144.57 ± 296.95 | AFO-NON | 0.4285 |
| | | FES | -365.52 ± 261.39 | FES-NON | 0.0621 |
| | | NON | -12.96 ± 333.411 | | |
| Step length (%bh) | | AFO | 135.26 ± 47.49 | AFO-NON | 0.7837 |
| | | FES | 199.39 ± 53.91 | FES-NON | 0.143 |
| | | NON | 144.06 ± 69.82 | | |
| Step duration (ms) | | AFO | 204.19 ± 96.67 | AFO-NON | 0.0515 |
| | | FES | 173.67 ± 37.63 | FES-NON | *0.0339 |
| | | NON | 138.47 ± 19.81 | | |
| Reaction time (ms) | | AFO | 239.14 ± 131.93 | AFO-NON | 0.5255 |
| | | FES | 328.39 ± 102.98 | FES-NON | 0.1365 |
| | | NON | 258.36 ± 66.14 | | |
| Second step failure (%) | | AFO | 23.81 ± 41.79 | AFO-NON | 0.9577 |
| | | FES | 66.67 ± 51.64 | FES-NON | 0.1312 |
| | | NON | 25 ± 45.23 | | |

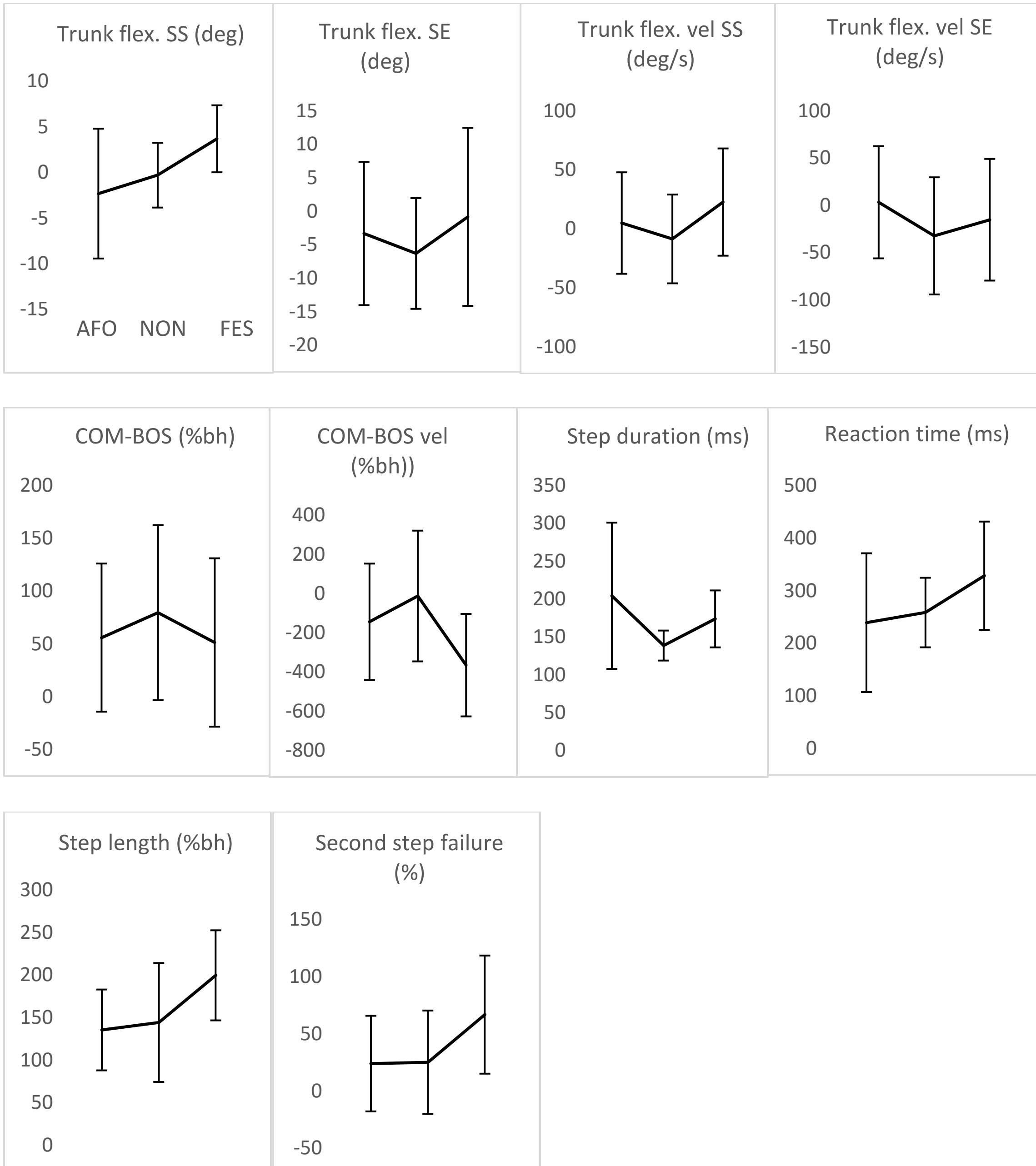


Figure 3.14: Comparison of compensatory stepping response of all users tested in their natural conditions at level 2 (i.e., AFO and FES users wearing their orthosis(W) and Non-users without any AFO(WO)). Abbreviations: flex=flexion, vel=velocity. SS=step start, SE=step end, bh=body height, COM=center of mass, BOS=base of support.
Analysis involved 20 data points for 7 AFO subjects, 19 data points for 6 FES subjects and 35 data points for 12 Non-users.

# 4 DISCUSSION

The purpose of this study was to investigate if the use of AFO and FES had an impact on fall rate and the ability to evoke a recovery step following anterior perturbations in long term chronic stroke users. In general, fall rate was not significantly impacted whether the users wore their assistive devices or not irrespective of the perturbation level (i.e., level 1 or 2). However, comparing the fall rate results at both perturbation levels (i.e., levels 1 and 2 combined) between AFO, FES and Non-users respectively revealed that AFO users recorded a significant high fall rate as compared to Non-users.

The fall rate difference between FES users and Non-users was not statistically significant. This indicates that while FES devices do not increase backward fall rate, AFO devices do when the fall rate for both perturbation levels were analyzed together. It should be noted that at the individual levels of perturbations delivered (level 1 or 2), no significant difference in fall rate was recorded among the groups.

Kinematic variables were assessed at the end of the first compensatory step following perturbation. No differences were reported in any of the kinematic variables assessed but for step duration between FES users and Non-users. FES users had a significant higher step duration as compared with Non-users. Increase step duration implies a delay in stepping response but this did not correlate to a high fall rate as expected. It is unclear the various factors that could possibly lead to this result being observed in FES users.

Although various studies conducted (Bethoux, et al. 2015; Nikamp et al. 2019; (Hausdorff and Ring 2008) report a high fall rate in AFO and FES users after device prescription, evaluating the kinematic response after the first compensatory step following anterior treadmill perturbations revealed no impact of the assistive device in either assisting or impairing chronic stroke users to recover from falling. This result is similar to previous work (Masood Nevisipour et al. 2019) which evaluated the impact of the use of AFO and FES devices in fall prevention amongst chronic stroke users following posterior treadmill perturbation.

The use of AFO and FES devices have been investigated to positively impact gait and static balance (Bethoux, et al. 2014; Doğğan et al. 2011; Kluding et al. 2013) in users with foot drop. However, these devices may not assist recovery of balance by promoting the eliciting of a compensatory step. To evaluate the effect of the use of AFO and FES devices, subjects were tested without wearing their assistive devices. Compared with wearing their assistive devices, removing them had no significant impact on the fall rate and compensatory stepping response.

## 4.1 Backward versus forward gait

Various studies have reported the importance of plantarflexion in helping to generate the necessary propulsion during forward walking.(Zelik and Adamczyk 2016; C. Peterson et al. 2011;Vistamehr et al. 2014). A recent study that compared fall rate in AFO and Non-users with chronic stroke when subjected to trip-like perturbations recorded a high fall rate in AFO users as compared with Non-users. The study concluded that, this result obtained could possibly be due to severe ankle impairments an AFO and users and the restriction of plantarflexion by the AFOs worn.

On the other hand, the main thrust during backward gait is provided by the hip and knee extensors( C. Peterson et al. 2011; Grasso et al. 1998). This study did not include the recording of activity of the hip and knee extensor muscles and the analysis of the joint angles of the hip and knee. Therefore, with regards to this current study, although other important kinematic variables that quantifies stability such as trunk stability, step length, step duration and COM-BOS (Crenshaw et al. 2012; Bhatt et al. 2006; Salot et al. 2016) were analyzed, no significant results was obtained that could possible explain the increased fall rate observed when AFO users were compared with Non-users at the combined perturbation levels. The cause of the high fall rate may be due to other factors such as the degree of extension of the hip and knee.

It is worthy stating that the biomechanics of backward walking pattern is different to that of forward. Forward walking stance is characterized by heel strike and toe off whereas backward walking stance begins with the toe first contacting the ground and the heel being lifted off last. Backward and forward gait is also impacted by the anatomic and functional asymmetry of the leg and foot. The toe articulates on the metatarsal joints and behaves as a deformable support whereas the tarsus represents a more rigid segment and articulates with the shank and leg.

Findings from various research works have postulated that forward and backward stepping may be controlled by different neurological and biomechanical constraints (Grasso et al.

1998, (Nonnekes et al. 2013). This may explain why the higher step duration observed in FES users did not translate to high fall rate as expected.

## 5 CONCLUSION

No significant difference was observed in fall rate when subjects were compared with and without the use of the assistive device, suggesting that the use of assistive devices neither increases the fall rate nor impairs the ability to evoke a compensatory stepping response. However, the increased fall rate in AFO users when compared with the Non-users in their natural conditions could likely be due to the angulation of the hip and knee which was not quantified in this study. FES uses observed an increase in step duration when compared with Non-users, but this did not translate to high fall rate.

# 6 LIMITATIONS AND FUTURE WORK

In this study, subjects only experienced stance-slip perturbations on a treadmill. Future studies should evaluate fall rate and compensatory stepping response during gait-slip perturbations on a moveable platform

The main thrust for forward backward movement is achieved by the action of the hip and knee extensors. Future studies should analyze the biomechanics of the hip and knee joint during backward stepping to find out if this will account for the high fall rate recorded in AFO users and the increased step duration in FES users.

Falls generally occur unconsciously and in situations where the victim is performing or focused on a different task. Future studies should design experiments that will involve a cognitive task in combination with the delivery of anterior perturbations. Our study also examined the compensatory stepping response after the first step. However, examining the compensatory stepping response of the second step following external perturbations in also worth considering for future studies.

In this study, each subject had the opportunity whether to initiate the compensatory step with or without the paretic leg. Future studies should design experiments that can cause slipping of both the paretic and non-paretic leg and measure its outcome.

Participants of this study are long-term AFO and FES users. It is unclear how this has impacted muscle use and the ability to evoke a compensatory step from the time of prescription. Future studies should evaluate whether long-term use of AFOs on muscle engagement and movement patterns have an impact on the compensatory stepping response and fall risk.

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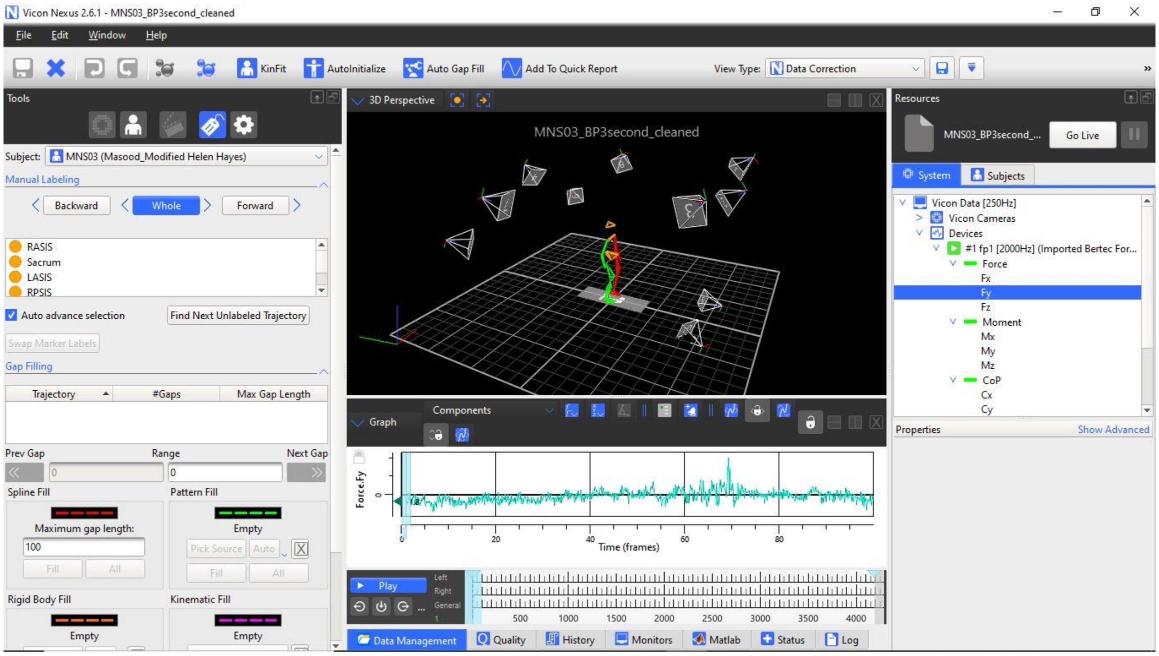
# APPENDIX A

# VICON IMAGES OF SUBJECTS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Tools
Subject:
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Backward
Whole
Forward
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Sacrum
LASIS
RPSIS
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Trajectory
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Prev Gap
Range
Next Gap
Spline Fill
Pattern Fill
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Empty
Pick Source
Auto
Fill
All
Rigid Body Fill
Kinematic Fill
Empty
Empty
3D Perspective
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Status
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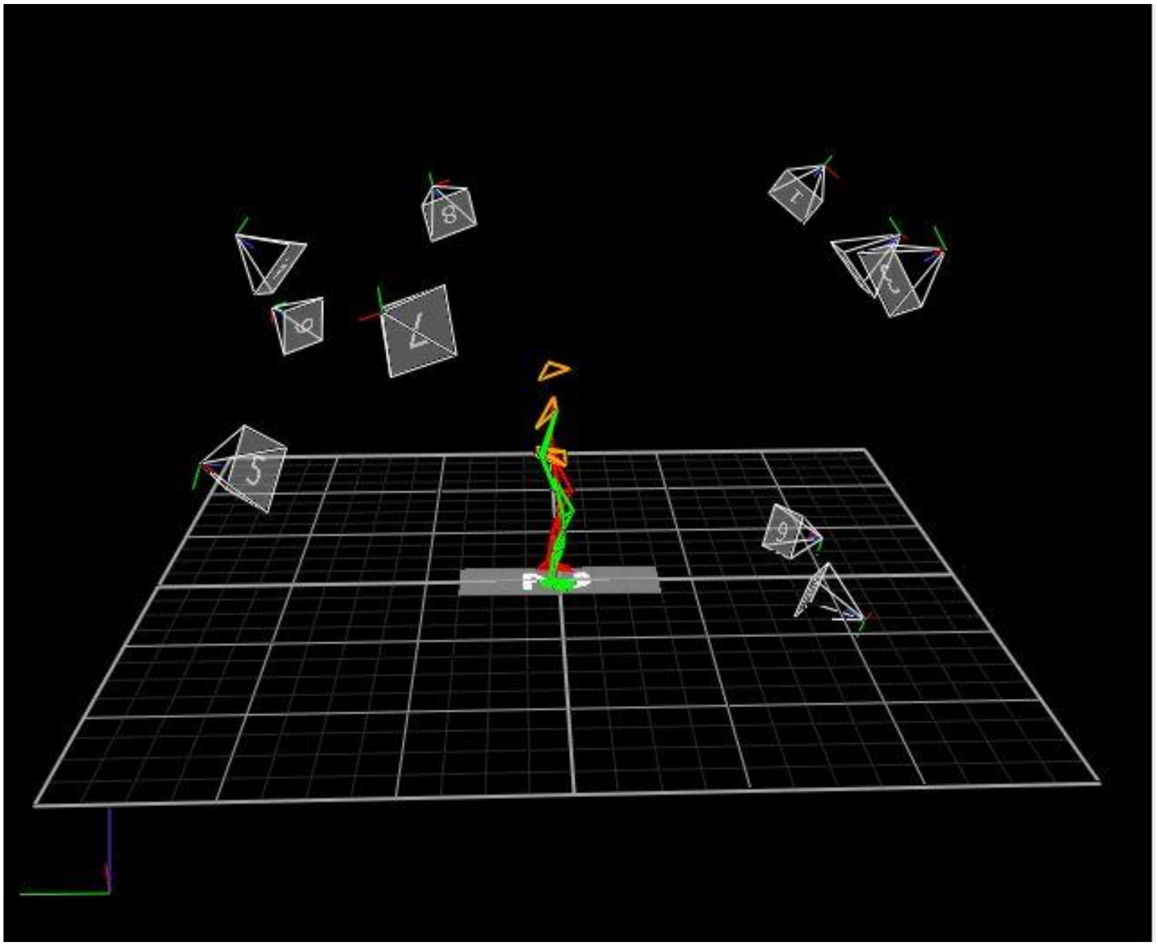

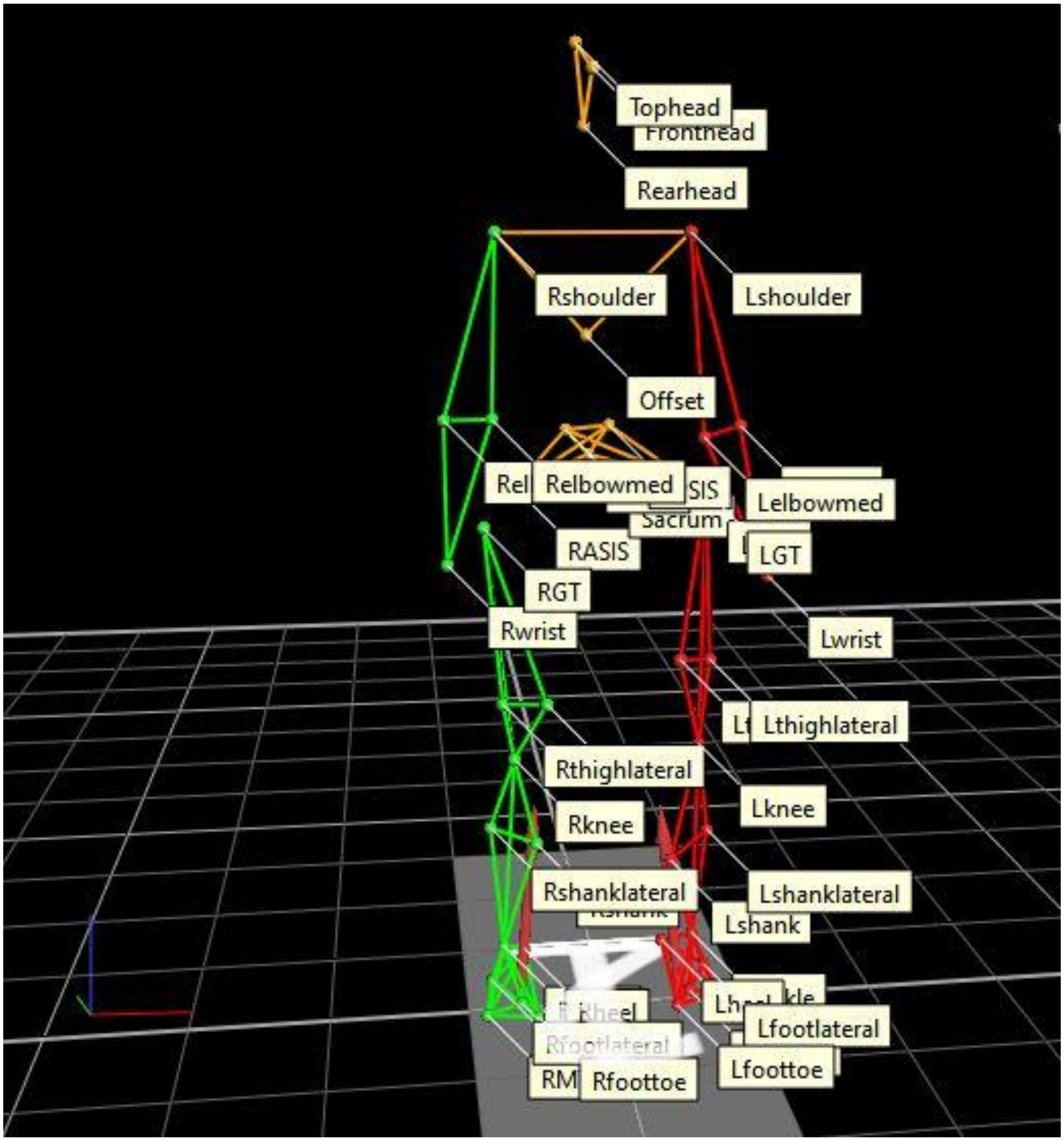
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Rearhead
Rshoulder
Lshoulder
Offset
Rel
Relbowmed
Lelbowmed
Sacrum
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LGT
RGT
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