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Quantifying Fear of Falling by Utilizing Objective Body Sway and Muscle Contraction Measures

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By

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ABSTRACT

Quantifying Fear of Falling by Utilizing Objective Body Sway and Muscle Contraction Measures

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Fear of falling (FOF) is a psychological condition that can lead to increased morbidity and mortality in the elder population. However, the subjective and multidimensional nature of FOF resulted in the limitations of existing FOF measurements, which could influence the quality of those studies. The present study aimed to quantify FOF by using objective center of pressure (COP) trajectories and muscle contraction of the lower extremity to compensate for those limitations. Nineteen young healthy adults (24 years ± 2.47) were recruited in the present study. Subjects were required to watch three 360-degree videos, one control video and two roller coaster videos, through virtual reality goggles during standing and sitting. One baseline trial without video and 6 trials with video were performed. Subjects were required to rate their FOF by a visual analogue scale after watching videos. Friedman test and Spearman's correlation analysis were used to assess the changes in COP and electromyography (EMG) under different video conditions. Increased FOF, increased COP root mean square and range, and decreased COP mean power frequency were observed during watching roller coaster videos. However, muscle contraction did not show significant changes. Roller coaster videos induced FOF and postural control change successfully. With the increased FOF, people adopted a postural control strategy with decreased body sway frequency and increased body sway amplitude. Our study provided evidence that 360-degree roller coaster videos

are effective tools to induce FOF; and body sway frequency and amplitude are sensitive parameters to quantify FOF.

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LIST OF ABBREVIATIONS

FOF	fear of falling
ADL	activity of daily living
FSE	falls-related self-efficacy
SAFFE	survey of activities and fear of falling in elderly
FES	fall efficacy scale
ABC	activities-specific balance confidence scale
EDA	electrodermal activity
COP	center of pressure
MPF	mean power frequency
SD	standard deviation
RMS	root mean square
Ta	tibialis anterior
AP	anterior-posterior
ML	medial-lateral
EMG	electromyography
Gas	gastrocnemius
Rec	rectus femoris
Ham	hamstring

CHAPTER 1: INTRODUCTION

Falls and Fear of falling (FOF)

The definition of a fall is "an unexpected event in which the participant comes to rest on the ground, floor, or lower-level".[1] In the United States, one in four older adults (>60 years) has at least one fall each year.[2] And 20% falls result in fatal and non-fatal injuries that require medical attention.[2] Common adverse health outcomes after falling are fractures, soft tissue injuries, traumatic brain injury, subsequent immobilization, activity avoidance, or even death. [3,4] It is estimated that 31.3 billion dollars are spent annually on fall injuries in the older population.[5] The cost will increase with the aging society in the United States.

Falls are related to multiple physiological, psychological, and environmental factors. FOF is one of the most common psychological factors that has a close and sophisticated relationship with falls. FOF and falls are both an independent risk factor and an adverse outcome of each other. Once people report FOF or a fall, a vicious cycle might form and impose tremendous debilitating effects on people.

FOF as a contributing factor to falls

FOF as a contributing factor to falls has not been understood completely. The activity-avoidance mechanism is considered the most acceptable model to explain why people with excessive psychological concerns about falling are at increased risk of experiencing subsequent falls.[6] Forty-four percent to eighty-two percent of older adults with FOF have self-imposed activity restrictions in their daily life due to the fear of losing balance.[7-11] Many physical and psychosocial characteristics predispose people to adopt self-limiting behaviors to prevent future falls and accompanying injuries. People with impaired pre-existing health status tend to limit their activities once they demonstrate fear about falling. Low self-perceived health[10] and comorbidities that impair balance[12] contribute to the predictability of activity restrictions in the population with FOF. Perception of the falling and its consequences also impact the FOF coping methods. Catastrophic thoughts about falls[13], knowing someone with falling experience[9], fear of losing independence[14], and worries about damaging personal identity[14] inhibit people from participating in daily activities, especially the events that can stimulate their fear of losing balance. People who have poor social support[9] tend to be more conservative and stop doing activities with which they feel unconfident.

Fear-related activity limitations will lead to subsequent falls by causing detrimental effects on functional performance and physical ability. Rantakokko et al.[15] found that people with fears of moving outdoors had slower walking speed; after 3.5 years of follow-up, those people demonstrated increased walking difficulty compared with people without fear. Reduction of activity participation also impairs other mobility functions and physical performance. Static standing[7], timed sit-to-stand[7,16], functional reach performance[17], the activity of daily living (ADL) performance[17], and muscle strength[17] are all negatively affected by the decreased activity level. Two prospective cohort studies investigated the causative relationship between functional performance and fear-related activity limitation. Despite the FOF and ADL performance baseline levels, fear-induced activity avoidance serves as an independent predictor of ADL disability.[7,18] And the severe activity restriction group demonstrated increased ADL disability compared to people with moderate activity restriction.[7] Regardless of the impairments resulting from fear-related activity avoidance, restriction of activity after FOF itself is also an independent predictor for future falls.[19]

Researchers also report other adverse conditions caused by fear-induced activity avoidance. The functional decline and the physical impairment secondary to fear-related activity restrictions also result in increased hospitalization, morbidity, and mortality. A sedentary lifestyle and decreased social interaction after activity avoidance also cause psychological problems. People who limit their activities because of FOF have a higher risk of depression and anxiety.[11,20] And the symptoms of depression and anxiety can reinforce the severity of functional decline and physical deconditioning.

Falls as a contributing factor to FOF

The role of fall contributing to FOF is self-exploratory by its name: FOF is an adverse psychological concern resulting from falls. Researchers initially observed FOF in the population with a history of falling and described it as a post-fall syndrome. The adverse consequences of falls people experienced or potential injuries they are afraid of can facilitate the generation of FOF. Another explanation of the FOF after fall is the impaired confidence in maintaining balance during daily activities after falling. A falling history is a prominent risk factor for the development of FOF.[21,22] For people without a history of falling, more predisposing factors are needed to trigger FOF.[23] Lee et al.[23] investigated the characteristics contributing to FOF by comparing people with and without a fall history. For the group with fall history, female and discomfort with the living environment are associated with FOF. In contrast, ten more factors relevant to age, comorbidities, and physical functions are correlated with FOF in people with no fall experience.

Other contributing factors and consequences of FOF

As suggested by Lee et al[23], FOF is not merely a by-product of falls. FOF can happen in the population without a history of falls. And a fall is just one of the adverse consequences induced by FOF. Gender, polypharmacy, health status, physical function, cognition, and psychological function are significant components predicting FOF.[21,26]

Female sex is consistently recognized as an independent predictor of FOF across studies.[21,23-26] Older women are at an elevated risk of reporting FOF than their male counterparts. The impact of gender on FOF is more than the different prevalence of FOF in female and male populations. Pauelsen et al.[26] even found the discrepancy between two genders about the characteristics predicting FOF. FOF in females is associated with polypharmacy, poor physical function, and negative perception about aging. But males who complain about FOF are those who demonstrate physical impairment and concern about the injury after falling. Comorbidities are quantified as the total number and detrimental effects of chronic conditions.[22,24] The level of the severity of comorbidities is positively associated with the risk of FOF.[22] This positive association might result from polypharmacy and poor self-perceived health due to multiple chronic conditions. Chronic illnesses like stroke[21], diabetes mellitus[23], and arthritis[23] can impair balance control and physical function performance and then induce fear of falling.

Physical function, mobility performance, cognition, and depression correlate with FOF bi-directionally. Disability of performing daily activities[22], gait abnormality[12], and impaired cognition[12] at the baseline are significantly related to the increased prevalence of FOF two years later. And people with FOF are more likely to develop balance problems [12], ADL disability [18,27,28], and declined mobility capacity [24] subsequently. The association between FOF and depression has also caught the attention of researchers. Depressive disorders were found to be associated with FOF in many studies [22,25,29,30]. Further investigations about their temporal relationship revealed that depression could facilitate FOF [12,22]. Based on the activity avoidance mechanism mentioned above, people with FOF are also at higher risk of depression due to social isolation, sedentary lifestyle, and reduced functional capacity.

FOF is a debilitating condition that can lead to increased morbidity, mortality, and subsequent impairments of functional performance and quality of life. More and more studies have been performed to investigate the different aspects of FOF. Choosing appropriate measurement tools of FOF is fundamental for those studies.

Measurements of FOF

Constructs of FOF

FOF, or less confusing - psychological concern about falls (because one of its constructs is FOF) is an umbrella conception that has various constructs. FOF, fear-related activity restriction, fall-related self-efficacy (FSE), and balance confidence are four primary constructs of FOF. Due to the multi-dimensionality of this umbrella term, there is no "standard" definition of FOF. The definition of FOF varies based on different constructs.[31] The description of the FOF construct is "fearful anticipation of a fall"[32]. Fear-related activity restriction construct developed from Tinetti and Powell: "FOF is lasting concern about falling that leads to an individual avoiding activities that he/she remains capable of performing".[33] FSE and balance confidence constructs derived from the operational definition of FOF, "low self-perceived efficacy or confidence at avoiding falls"[34]. The FSE, also known as falls efficacy, is people's efficacy or confidence to perform activities without falling. Balance confidence is confidence in one's ability to maintain balance and to remain steady while moving. The relationship between FSE and balance confidence is controversial. Some researchers[35,36] regarded them as two different constructs of FOF. But other researchers considered them as one construct as fall-efficacy [31] or balance efficacy[37] and unified them as "individual's confidence or belief in their ability to perform specific activities without losing balance or falling".[31]

Current Measurements of FOF

Those constructs sometimes are used interchangeably, and they are all referred to as "FOF". However, the constructs are not the same and should be measured and understood separately. For example, fall efficacy and balance confidence are not identical to FOF. People may report no fear in performing daily activities but are still worried about falling. Therefore, different measurements of FOF have been developed based on the different constructs of FOF.

The most common measurement of the FOF construct is a single question. A single question like "are you afraid of falling?" categorizes people into a "fearful group" and a "non-fearful group".[11,21,22] Although easily implemented, a one-item question cannot detect the severity of the fear. The utilization of the Likert scale overcomes this limitation.[18 23,38] Another shortcoming of one simple question is uninformative due to asking fear without considering contexts. As a result, it might underestimate the prevalence of FOF compared to other measurements.[39] Survey of activities and fear of falling in elderly (SAFFE) is another measurement tool for the FOF construct.[39] SAFFE provides information about both the FOF and the activity avoidance caused by FOF. The modified version of SAFFE has eliminated several items to increase the discriminant validity in the population with better function.[14] The University of Illinois at Chicago fear of falling measure assesses the level of concern about falling for 16 activities using a 3-point Likert rating scale.[40] Geriatric fear of falling measure[41] works as a quick screening tool for the FOF related psychometric symptoms and perception about fall prevention for elder adults living in Taiwan.[42] The fall efficacy scale (FES) consists of 10 daily activities.[34] It is a widely used assessment to investigate risk factors, consequences, and intervention programs related to falls efficacy.[43-45] However, because FES only includes basic activities, it is not sensitive to capture fearful perception about falling in the higher-function group. Several amended versions of FES complement FES and fulfill different purposes.[46-48] The mobility efficacy scale and the gait efficacy scale assess the efficacy of safe mobility and gait.[49,50] Activity balance construct is measured by activities-specific balance confidence (ABC) scale.[51] ABC includes a broader spectrum of activities to address the limitations of FES. Compared to FES, ABC has better responsiveness and is more suitable for the higher-function population. There are also modifications of ABC to fulfill the requirements for various settings and populations.[52,53]

Although FOF, fear-related activity restriction, fall-related efficacy, and balance confidence are the most studied constructs of fall-related psychological concern. Concern about falling is also related to the consequences of falls, the individual's perceptions about falls, and the feeling of control over falls. The consequence of falling scale[14], perceived control over falling scale[54], and perceived ability to manage falls scale[54] can quantify those constructs of FOF.

Limitations of current measurements of FOF

There are several limitations to the current measurements of FOF. The first limitation is the lack of comparability among various measurements. Measurements mentioned above are designed to focus on different constructs of the FOF. And the measurements of the same construct differ in the wording of the question, listing activities, rating scales, or administration methods (interview or self-report). [31,35] Current studies exploring the prevalence, risk factors, consequences, and interventions of FOF have utilized different assessments to evaluate people's concerns about falling. As a result, different psychometric properties of the measurements generated the inconsistent study results and added the difficulty of generalizing research findings of FOF. Reported risk factors of FOF are not consistent across constructs.[55] The geriatric fear of falling measure has higher sensitivity than the FES and ABC in detecting the improvement of

FOF resulting from a fall-prevention program.[42] Due to the different sensitivities of measurement-s[42,56,57], an intervention program can alleviate the fall-related concern in one study but appear useless in another study that uses a different measurement. The calculated prevalence of FOF is also of high variance among studies. The second limitation of current measurements is the self-report bias. All current measurements require people to recall or imagine their psychological or physical responses in certain situations. Recollection is subject to memory loss. Uemura et al.[58] found that people with memory loss will report less FOF because of the recalling difficulty. Self-report is also influenced by individuals' experience. A study conducted by Myers and his colleagues[37] found that the frequency of doing a specific activity will affect activity-related confidence. People might overestimate their fall efficacy of activities that are not common in their daily lives. Other physical and psychological factors can also impact self-reported outcomes. Two groups of researchers[59,60] compared the observed functional ability and self-reported functional ability. The comparison indicated that many physical and psychological factors influence self-report after adjusting for the observed function level. And in general, people tend to report their function better than what health care providers observe.[60] Feuering et al.[60] also found a systematic bias in self-report. The last limitation is that how people understand and perceive questions can influence subjective measurement results. Therefore, educational level, cultural background, and the language barrier can impact the accuracy of the measurement.

Limitations of current measurements call for a new objective assessment tool for FOF to eliminate bias from self-reports and subjectivity. Also, an objective measurement can serve as a benchmark for subjective measurements to increase the comparability among measurements. Motor control strategies related to psychological concern about falling has been investigated and provided a novel perspective to measure FOF objectively.

Motor control

Applications of motor control

Motor control is "the ability to regulate or direct the mechanism essential to movement".[61] Systems theory, also called dynamic systems theory, describes motor control as a complex process that requires interactions of various systems.[62] Those systems include both internal systems and external systems.[63,64] Motor (neuromuscular synergy and musculoskeletal function), sensory (sensory integration, central sensory processing, and periphery sensory collection), and cognition (problem-solving, planning, attention, and emotion) are all internal systems that are essential for motor control.[65] Task and environment fall into the external system category. Because motor control is a dynamic process, changes in internal or external systems may result in adjustments of postural control strategies. Vice versa, changed postural control can indicate underlying system insufficiency including changed psychological concern - FOF.

Standing motor control and fear-related psychological concern

The relationship between postural control and psychological concerns about falling were frequently studied in standing.[66-73] Real and virtual elevated standing surfaces were successful in inducing psychological concern about falling.[69] Results of subject self-reported measurements and objective measurements of body arousal represent the psychological status of subjects. Self-reported measurements include subjective numerical rating (from 0-100 or 0-10) or questionnaire for fear, balance confidence, anxiety, and perceived stability.[66-68] Manifestations of body arousal are elevated electrodermal activity (EDA), blood pressure, and heart rate.[69,70] Center of pressure (COP) excursions, center of mass trajectories, muscle contraction, muscle co-contraction, and joint angle are parameters of postural control.[66,67,71]

The relationships between standing balance control and psychological concern about falling have been reported across studies. With the presence of FOF, people tended to use “stiffness strategies” by adopting increased tibialis anterior (Ta) contraction, greater COP mean power frequency (MPF), and reduced COP standard deviation (SD) and root mean square (RMS). In the visual height intolerance population, FOF during standing on different surfaces (height of 15 meters and 0 meters) had a moderate but significant positive correlation with muscle contraction of Ta.[66] In a study of postural control of healthy young adults, people reported greater anxiety, increased FOF, decreased balance confidence, and had higher EDA and changed COP trajectories during standing at the elevated surface (3.2m).[68] And their balance confidence negatively correlated with MPF of COP in the anterior-posterior (AP) plane.[68]

Taylor et al.[69] studied the postural control of standing in real and virtual heights. Both virtual and real heights stimulated greater FOF, EDA, anxiety, and lowered balance confidence and perceived stability. And the changes in EDA and FOF were more obvious in the real environment. Regardless of virtual or real environments, the surface height also affected AP and medial-lateral (ML) body sway. COP-MPF increases and COP-RMS decreases with the elevated surface. Unfortunately, the correlation between psychological responses and physiological COP changes was not investigated in this study. A study that compared postural adaptations in young and older adults used multiple heights (5 levels).[70]

Young and older adults have similarities and differences in their psychological and physiological responses.[70] AP-COP MPF and AP-COP SD had a positive and a negative relationship with elevated height, respectively. The change of AP-COP MPF had an upward trend along with the increased standing height in both young and older populations. In contrast, the decreasing AP-COP SD was scaled to raised standing surfaces in young adults only. And even though the AP-COP SD in older adults did not decrease continuously, the AP-COP SD in the lowest height trial was significantly larger than that in the highest standing trial. Correlation analyses were conducted based on data pooled from two groups. Anxiety had a positive linear correlation with ML-COP SD and a negative linear correlation with blood pressure change. Body arousal (blood pressure change) also correlated with postural responses (AP-COP SD and ML-COP SD).

Some studies only investigated the static postural control strategies on elevated height without explicitly reporting the psychological concern rating.[72,73] They reached similar conclusions that the increased postural threat is related to higher sway frequency, decreased sway variability, and increased TA contraction. COP-MPF increased and COP-SD decreased with raised standing surfaces. And the changes of MPF and SD were scaled to the increased height.[72] More intensive contraction of TA was generated in the increased height.[73]

Consistent findings cross studies provide potential of quantifying FOF by utilizing parameters of motor control under fearful conditions. However, three challenges should be addressed to find the appropriated level of FOF, sensitive balance control parameter(s), and the way to compensate for people intolerable to standing to develop the objective measurement of FOF by using the COP or muscle activity parameters.

Obstacles for the development of objective measurement of FOF

The appropriate level of “fear” to be induced is unclear as well as the method to induce the fear. Previous studies had different experimental setups and utilized different height of standing surface. And the level of psychological concern of falling can impact the relationship between balance strategy and subjective reports of FOF. Sturnieks et al.[74] reported that while standing on a 0.65 m height, people will have increased FOF but no change in body sway frequency. Only marginal statistical changes of COP-SD (p=0.19) and COP-MPF (0.08) were noted when people stood on an 81 cm-height.[73]

Davis and his colleagues[75] found that standing on a 3.2-meter height only induced significant FOF in about one third of people. They also questioned the efficacy of the utilization of elevated height to induce FOF in previous studies.[75] To develop a method to quantify FOF by objective kinematic or kinetic parameters, inducing sufficient FOF to stimulate the altered balance control should be accomplished first. The second obstacle is the choice of objective parameters. With increased FOF, people tend to tighten their body sway by reducing the amplitude of COP change. COP-RMS and COP-range both reflect the amplitude of body sway; however, only the change of COP-range was reported as significant when people standing on a balcony of 15-m.[66]

Huffman[68] reported that people demonstrated increased sway frequency but unchanged sway amplitude while standing on a surface of 3.2 m compared to level surface. Even though studies revealed that fall-related fear in general induce a postural change with increased sway frequency and decreased sway amplitude, different parameters tend to have different sensitivities to the fall-related psychological concerns (e.g., FOF, balance confidence, and perceived stability). The third obstacle is the applicability of standing balance measurement in the population with impaired standing balance control. FOF is common in the population with impaired balance.[21,23] Standing still for prolonged time could be challenging for this population; and people may demonstrate altered postural control strategies if they are not able to maintain balance during static standing.

Conclusion

The development of an objective assessment tool of FOF is necessary due to the limitations of existing measurements. Objective measurement of postural control in response to FOF is a promising option based on current research findings. Standing postural control is a simple but informative method to reflect changes in numerous internal and external systems related to the human body and movement. The psychological concern is one of those systems. Consistent COP trajectory alternation and muscle activation in response to falling concerns were reported among studies[66,68-70,72,73]. COP and muscle activation changes provide a potential perspective to measure FOF. Implementation of real or virtual postural threats in standing can elicit a feeling of instability and concerns about falling effectively and safely. And fearful conditions stimulated increased TA contraction, greater COP MPF, and reduced COP SD and COP RMS. Previous studies also provided a fair amount of evidence that postural change might be scaled to psychological concern and can be used to quantify FOF. However, there are several questions needed to be addressed during the development of this objective method. The appropriate level of induced fear and choices of parameters needed to be determined. And modifications of this method might be necessary for the populations with impaired standing balance.

Therefore, the present study utilized virtual 360-degree dynamic roller coaster environment to induce FOF. Those videos consist of both up-and-down and rotational changes. Compared to a static elevated standing surface, a dynamic environment is more similar to a real situation when people experience a fall. And the virtual change of height in roller coaster video is much higher than the standing surface in those studies mentioned above, which should generate higher FOF compared to previous studies. Three video conditions were utilized and both electromyography (EMG) and COP were collected in the present study in order to investigate the sensitivity of parameters to the changed FOF in different conditions. Experiments were conducted in standing and sitting to investigate the replicability of the method in sitting for population with impaired standing balance. The hypotheses of the present study included: 1) 360-degree videos of roller coaster will induce increased FOF compared to control condition, 2) subjects will demonstrate increased COP-MPF, Ta contraction, and muscle co-contraction of the lower extremity, and decreased COP-range and -RMS with increased fear in both standing and sitting conditions, and 3) FOF will be correlated with COP-MPF, -range, and -RMS in both standing and sitting conditions.

CHAPTER 2: METHOD

Participants

A total of 19 healthy young adults were recruited in this study. Subjects were excluded if they have any symptoms and conditions including 1) musculoskeletal, neuromuscular disorders or any other diseases that influence balance, 2) dizziness, vertigo, headache, and motion-sickness during watching the 360-degree roller coaster videos, 3) cognition impairments, and 4) pregnancy. All subjects had normal or corrected vision. This study was approved by the Institutional Review Board of University of Nebraska Medical Center. Informed consent and verbal explanations were provided to each subject prior to the experiment.

Virtual environment

Three 360-degree videos were used in this study: one control (30-second) video and two roller coaster (Ma: 120-second and Pa: 80-second) videos. The control video was taken in the room where the study was conducted, which is a room without any moving objects or people. And roller coaster videos were taken on the real roller coasters in an amusement park. Ma is 205 feet in height with two intense hills, several small hills and one helix. The height of Pa is 149 feet; and Pa has one intense hill, one big loop, and one quick corkscrew. Ma is higher but with less rotations than Pa. The virtual environments were created by playing the 360-degree video on a smartphone that was placed inside a pair of virtual reality goggles. And to increase the sense of reality and immersion, the audio of the roller coaster machine squeaking was played in an acceptable volume determined by each subject.

COP and EMG measurement tools

Wii balance board (WBB: Nintendo, Redmond, WA) was used to record COP trajectories. WBB is a portable and relatively inexpensive device to measure COP. Great reliability and validity of COP measurements by WBB were confirmed by Clark et al.[76] The interclass correlation coefficients between the COP trajectories measured by "gold standard", force platform, and WBB range from 0.77-0.89 with different standing conditions;[76] and the test-retest reliability of COP with WBB ranges from 0.66-0.91 during various standing conditions.[76] EMG signals were collected via the Trigno™ wireless EMG system (Delsys Inc., Natick, MA) with a sample frequency of 2000Hz. Muscle contraction activities of Ta, medial gastrocnemius (Gas), rectus femoris (Rec), and medial hamstring (Ham) were recorded through the sensors attached on the dominant leg of subjects (Figure 1). Skin preparation was performed before the data collection including cleaning by an alcohol wipe and shaving if necessary. Sensor placement was performed by a same research personnel for all subjects. Sensors were placed on the biggest muscle belly during individual muscle contraction against manual resistance.

Protocols

Each participant completed seven trials: one baseline trial of quiet standing with no video, three sitting trials with three videos, and three standing trials with three videos. (Figure 2) The baseline trial was performed first to collect the baseline EMG data. The order of other 6 trials were random. Six identical cards, with the name of each trial (control-stand, Pa-stand, etc.) written on them, were folded. Each subject was instructed to place the folded cards from left to right as the order of trials. Body sway and muscle contraction were both obtained during the following 6 trials with videos.

During the baseline trial, each subject stood on the floor with EMG sensors on the target muscles for 30 seconds. Only EMG data were collected during the baseline trial. For sitting and standing trials, subjects were asked to sit or stand on the WBB in a way that was the most natural to them. They were also required to act naturally during watching videos and not allowed to move their feet during standing trials or move buttock during sitting trials. Subjects also needed to sit without leaning on the back of the chair during sitting trials.

After each trial (except the first trial for baseline EMG data), one question “how much fear do you feel that you might fall or lose balance during watching the video?” was asked. And a visual analogue scale was used to quantify the fear. Each subject was asked to place a mark on a 10-cm line with ticks for every 1-cm interval. Zero indicates no fear at all, and 10 indicates extreme fear. All six 10-cm lines were put on one paper from top to bottom. Answers were covered after they rated FOF of each trial so that subjects were not able to see FOF of previous trials when they rated the current video.

One-minute break was assigned between trials. Subjects could request a longer break if they needed. Because the roller coaster videos consisted of abrupt changes in terms of direction and height, subjects were under a potential risk of motion sickness and losing balance while watching the videos. One research personnel stood next to the subject during the data collection for protection. The distance between the subject and the research personnel was around 30 cm so that she/he did not touch subjects and could catch the subject if subjects lost balance. No adverse events such as headache, vertigo, nausea, and losing balance were reported or observed during and after experiments.

Figure 1: EMG placement in the front view (left) and posterior view (right)

Figure 2: Sitting trial (left) and standing trial (right)

Data collection

COP data were collected from a WBB sampling at 100 Hz. COP-range, -MPF, and -RMS in ML and AP directions were calculated for each trial (except the baseline trial). COP-range indicates the maximal distance between the two farthest points in COP trajectories in ML and AP directions. To calculate MPF, Fourier transformation and power spectral density were performed first. Then the following equation was used.

$f_{mean} = \frac{\sum_{i=0}^{n} I_i f_i}{\sum_{i=0}^{n} I_i}$ where f_{mean} indicates mean frequency, n indicates the number of frequent bins in the spectrum, f_i indicates the frequency of the spectrum at bin i of n, and the I_i indicates the intensity of spectrum at bin i of n. RMS was calculated by the equation: $RMS = \sqrt{\frac{1}{n}\sum_i x_i^2}$ in which n indicates the number of measurements and x_i indicates each value. The EMG data were collected at a sample frequency of 2000 Hz. Because EMG raw data have low frequency noises that will influence the data analysis, the raw data were detrended by a band pass filter ranging from 10Hz to 500Hz. Then the data were filtered by 6 Hz Butterworth bandpass. The average muscle activity of each muscle in each trial was normalized by averaged baseline muscle contraction by the algorithm:

$$averaged\ muscle\ activity = \frac{(summed\ actitivy\ of\ muscle\ X)/(time\ of\ the\ trial)}{(basline\ summed\ activity\ of\ muscle\ X\ )/(time\ of\ the\ control\ trial)}$$. The muscle co-contraction for each trial was calculated by the algorithm:

$$Co-activation = \frac{2*(summed\ Rec + summed\ \ Ta)}{summed\ Rec + summed\ Ham + summed\ Ta + summed\ Gas}\ .$$

Statistical analysis

Sitting trials and standing trials were analyzed separately. The normality of variables was explored by histogram observation and Shapiro-Wilk test (table 1 and table 2). Due to the violation of the normality, Friedman test was used to investigate the effect of the 360-degree videos on FOF, COP-range, COP-MPF, COP-RMS, averaged muscle activity of each muscle, and muscle co-activation. The effect sizes of the results were calculated by the Kendall's W test. Post-hoc test was performed by the Wilcoxon Signed Ranks test if the effect of videos was significant. Then, Spearman's correlation analysis was performed to explore the correlational relationship between FOF and postural control parameters (COP-range, COP-MPF, COP-RMS, averaged muscle activity of each muscle, and muscle co-activation of each trial). A significance level of less than 0.05 was used. Shapiro-Wilk test, Friedman test, Kendall's W test, Wilcoxon Signed Ranks test, and correlation analysis were performed by the SPSS (Version 25; IBM Corp., Armonk, NY).

Table 1: Normality results of all parameters during standing condition

Shapiro-Wilk test	p-values
FOF	<0.001
Rec	0.009
Ham	<0.001
Gas	0.004
Ta	<0.001
Muscle co-contraction	0.035
COP-range ML	0.002
COP-range AP	<0.001
COP-RMS ML	<0.001
COP-RMS AP	0.014
COP-MPF ML	0.002
COP-MPF AP	<0.001

FOF: fear of falling; Rec: rectus femoris; Ham: hamstring; Gas: gastrocnemius; Ta: tibialis anterior; COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

Table 2: Normality results of all parameters during sitting condition

Shapiro-Wilk test	p-values
FOF	<0.001
Rec	<0.001
Ham	<0.001
Gas	<0.001
Ta	0.004
Muscle co-contraction	<0.001
COP-range ML	<0.001
COP-range AP	<0.001
COP-RMS ML	<0.001
COP-RMS AP	<0.001
COP-MPF ML	<0.001
COP-MPF AP	<0.001

FOF: fear of falling; Rec: rectus femoris; Ham: hamstring; Gas: gastrocnemius; Ta: tibialis anterior; COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

CHAPTER 3: RESULTS

Demographic overview of subjects was reported in the table 3. Friedman test results and correlation results were given from table 4 to table 7. The error bars of the comparisons of COP parameters were also demonstrated in the figure 3 and figure 4.

Table 3: Demographic characteristics of subjects

	Mean	SD	Range
Female (n, %)	12	63.16%	
Age, year	24	2.47	20-31
Weight, Kg	74.55	21.39	44.00-124.70
Height, cm	173.32	9.70	159.00 -200.70

Friedman test results

The Friedman test results were presented in the table 4. Friedman tests revealed significant video effects on reported FOF during sitting ($p<0.001$). Roller coasters increased FOF than control condition (p_{Pa} <0.001 and p_{Ma}<0.001). Reported FOF was significantly higher in Pa than in Ma ($p=0.013$). None of the four muscles were influenced by videos. In addition, no significant change in muscle co-activation was found during watching different videos. In contrast, significant effects of videos were revealed in COP parameters. Subjects reduced their body sway frequency in both ML ($p=0.008$) and AP ($p<0.001$) directions during roller coaster conditions. Pa significantly increased body sway frequency than Ma in AP direction ($p=0.027$) and no difference in body sway frequency was noted between two roller coaster videos in ML direction.

COP-range and COP-RMS are indicators of the body sway amplitude. Significant effects of videos were observed in both parameters and in both ML (p_{range}<0.001, p_{RMS}=0.003) and AP (p_{range}=0.001, p_{RMS}=0.008) directions. With the comparisons of the videos, Ma induced increased COP-range compared to control video in both ML and AP directions (p_{ML}=0.001, p_{AP}=0.002); and COP-range in Pa was also higher than in control condition (p_{ML}=0.004, p_{AP}=0.005). Similar with COP-range, subjects increased COP-RMS in both directions during watching Ma (p_{ML}=0.005, p_{AP}=0.01). Compared to control video, Pa video increased the COP-RMS only in ML direction (p=002). Body sway amplitude was not different between two roller coaster videos.

Table 4: Friedman test results in sitting

	Effect size	p-value	Pairwise comparisons (p-value)
FOF	0.635	< 0.001*	Control < Pa (< 0.001) Control < Ma (<0.001) Ma < Pa (0.013)
Rec		0.801	None
Ham		0.249	None
Gas		0.946	None
Ta		0.486	None
Muscle co-contraction		0.348	None
COP-range ML	0.452	<0.001*	Control < Pa (0.004) Control < Ma (0.001)
COP-range AP	0.385	0.001*	Control < Pa (0.005) Control < Ma (0.002)
COP-RMS ML	0.310	0.003*	Control < Pa (0.002) Control < Ma (0.005)
COP-RMS AP	0.252	0.008*	Control < Ma (0.01)
COP-MPF ML	0.252	0.008*	Control > Pa (0.002) Control > Ma (0.018)
COP-MPF AP	0.399	< 0.001*	Control > Ma (0.002) Pa > Ma (0.027)

* indicates p-value < 0.05

FOF: fear of falling; Rec: rectus femoris; Ham: hamstring; Gas: gastrocnemius; Ta: tibialis anterior; COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

Similar results were found in standing condition (Table 5). FOF differed between videos (p<0.001). Subjects reported increased FOF with roller coaster videos than control video (p_{Pa}<0.001, p_{Ma}<0.001). FOF induced by Pa was significantly higher than by Ma (p=0.006). None of the EMG measures were significantly impacted by videos. Effect of videos were presented in body sway parameters in both ML and AP directions. Effects of video on body sway frequency were observed in both directions (p_{ML}=0.029, p_{AP}=0.021). Body sway frequency with Pa was higher than control condition in both ML and AP directions (p_{ML}=0.013, p_{AP}=0.016). Significant effects of video on the amplitude of body sway were reported in COP-range in ML direction (p<0.001), COP-range in AP direction (p=0.001), and COP-RMS in AP direction (p<0.001). Two roller coaster videos were able to increase the amplitude of body sway consistently among those parameters. Post-hoc comparisons indicated that Ma induced significantly higher COP-range than Pa in AP direction (p=0.044).

Table 5: Friedman test results in standing

	Effect size	p-value	Pairwise comparisons (p-value)
FOF	0.677	<0.001*	Control < Pa (<0.001) Control < Ma (<0.001) Ma < Pa (0.006)
Rec		0.846	None
Ham		0.249	None
Gas		0.311	None
Ta		0.348	None
Muscle co-contraction		0.513	None
COP-range ML	0.634	<0.001*	Control < Pa (<0.001) Control < Ma (<0.001)
COP-range AP	0.501	<0.001*	Control < Pa (<0.001) Control < Ma (<0.001) Pa < Ma (0.044)
COP-RMS ML		0.196	None
COP-RMS AP	0.435	<0.001*	Control < Pa (<0.001) Control < Ma (0.014)
COP-MPF ML	0.186	0.029*	Control > Pa (0.013)
COP-MPF AP	0.202	0.021*	Control > Pa (0.016)

* indicates p-value < 0.05

FOF: fear of falling; Rec: rectus femoris; Ham: hamstring; Gas: gastrocnemius; Ta: tibialis anterior; COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

Effect size of Friedman test results were also showed in the table 4 and table 5. With the classification from Cohen[77], most parameters generated at least moderate level of effect (>0.3). High video effects (>0.5) were noted on FOF in both sitting and standing and COP-range in standing. Low to moderate effect size (0.1-0.3) were noted in COP-MPF in both ML and AP directions during standing, COP-MPF in ML direction and COP-RMS in AP direction during sitting.

Correlation results

Significant correlations were found between the COP measures and the subjective FOF in sitting (Table 6). Subjects demonstrated reduced body sway frequency in ML direction with increased FOF (r=-0.512, $p<0.001$) (Figure 5). For the COP-range and the COP-RMS, both represent the amplitude of body sway to some extent, only the COP-RMS in ML direction was positively correlated to FOF. Increased COP-RMS was associated with higher FOF (r=0.523, $p<0.001$) (Figure 5). There was no significant correlation between body sway measures in AP direction and FOF. In addition, no correlation was found between EMG parameters and FOF in sitting.

Similar results were observed in standing (Table 7). Significant correlations were reported between COP-RMS (r=0.372, $p=0.004$), COP-range (r=0.322, $p=0.015$), and COP-MPF (r=-0.309, $p=0.019$) and FOF in ML direction (Figure 6). Subjects adopted decreased body sway frequency and wider body sway range and amplitude in ML direction with increased FOF. Again, no COP parameters in AP directions and EMG measures were found to be correlated with FOF in standing.

Table 6: Correlation results in sitting

	Spearman's rank correlation coefficient	p-value
Rec	-0.222	0.107
Ham	-0.139	0.317
Gas	-0.043	0.757
Ta	-0.212	0.124
Muscle co-contraction	0.161	0.246
COP-range ML	0.069	0.061
COP-range AP	0.170	0.206
COP-RMS ML	0.523	<0.001*
COP-RMS AP	0.024	0.860
COP-MPF ML	-0.512	<0.001*
COP-MPF AP	-0.253	0.057

* indicates p-value < 0.05

Rec: rectus femoris; Ham: hamstring; Gas: gastrocnemius; Ta: tibialis anterior; COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

Table 7: Correlation results in standing

	Spearman's rank correlation coefficient	p-value
Rec	-0.063	0.651
Ham	0.031	0.827
Gas	0.012	0.933
Ta	0.043	0.760
Muscle co-contraction	-0.141	0.308
COP-range ML	0.322	0.015*
COP-range AP	0.191	0.155
COP-RMS ML	0.372	0.004*
COP-RMS AP	0.219	0.101
COP-MPF ML	-0.309	0.019*
COP-MPF AP	0.037	0.787

* indicates p-value < 0.05

Rec: rectus femoris; Ham: hamstring; Gas: gastrocnemius; Ta: tibialis anterior; COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

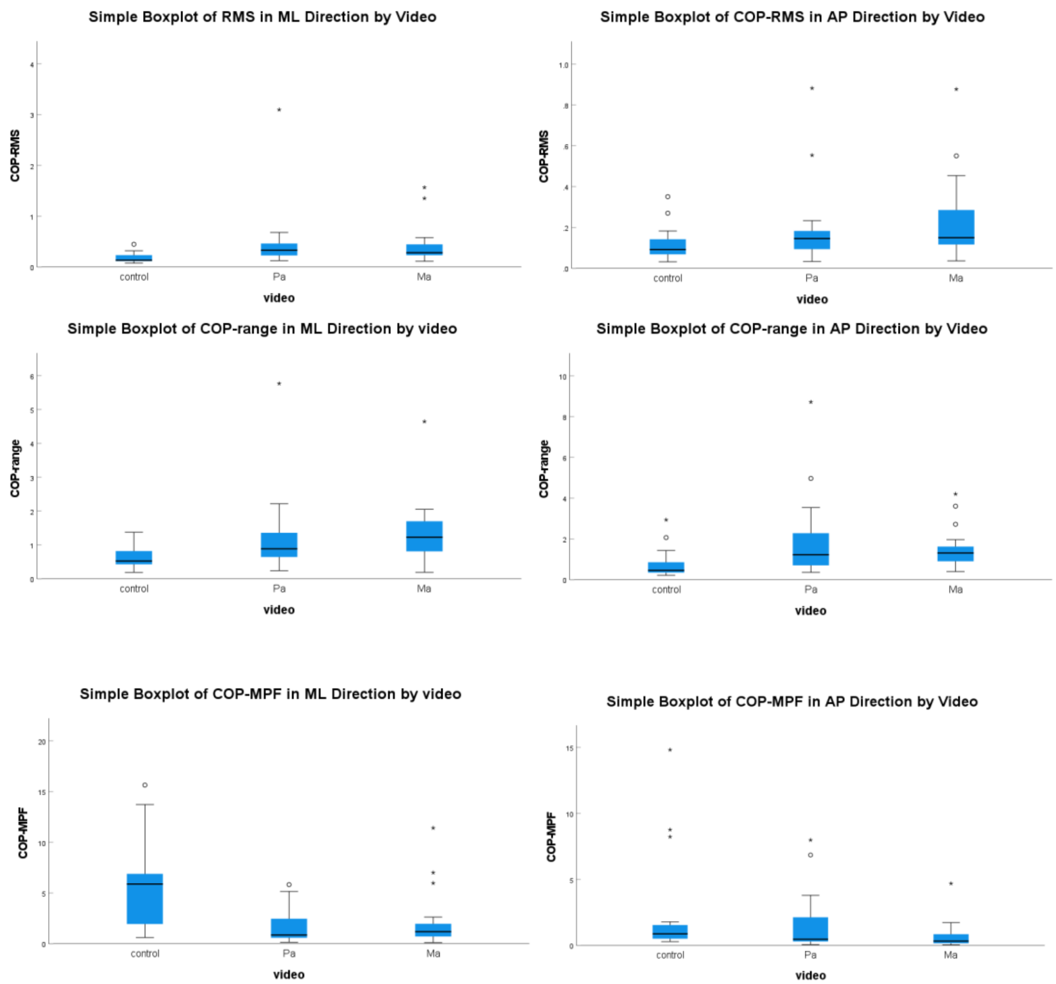

Figure 3: Box plots of COP parameters in sitting.

COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

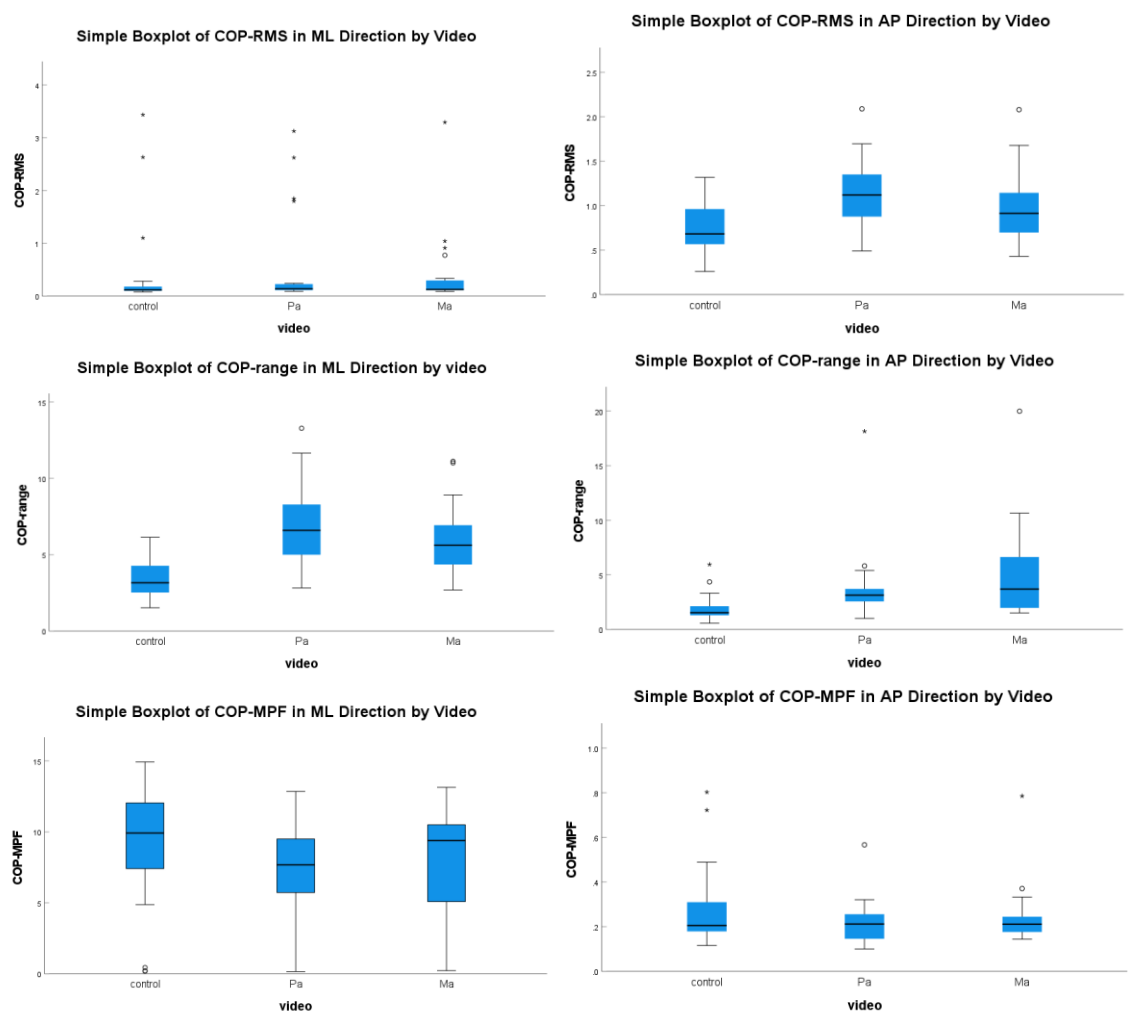

Figure 4: Box plots of COP parameters in standing

COP: center of pressure; ML: medial-lateral; AP: anterior-posterior; RMS: root mean square; MPF: mean power frequency.

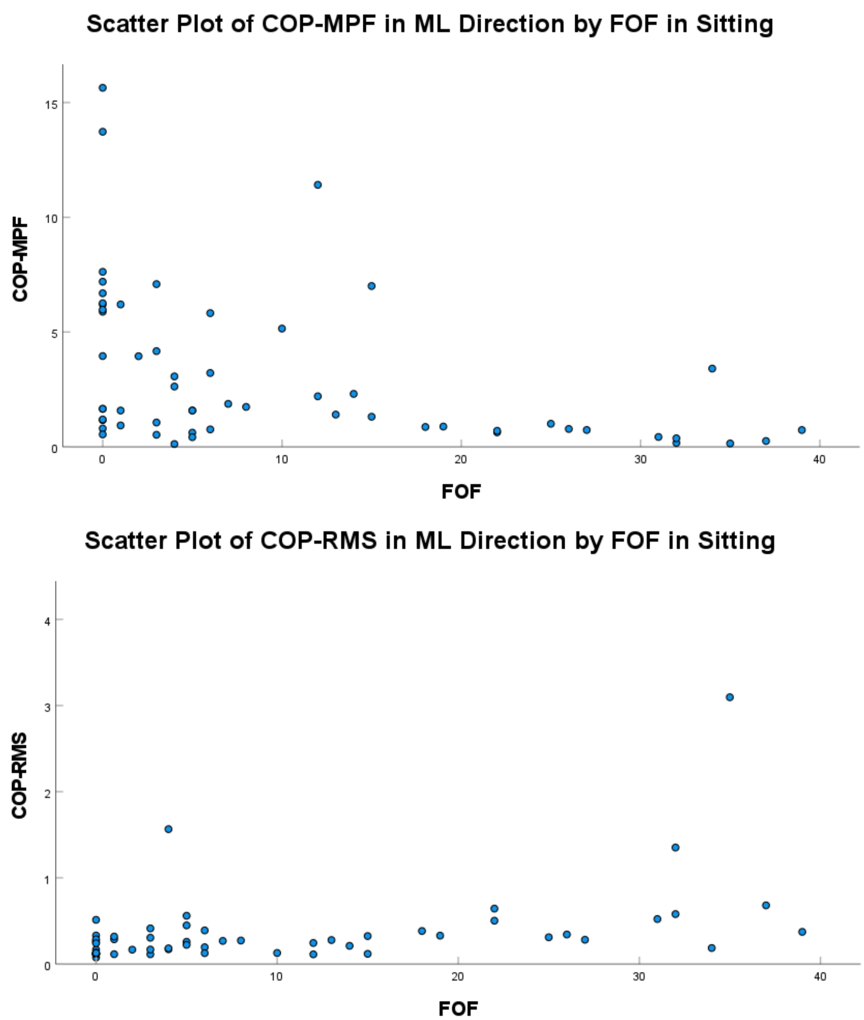

Figure 5: Scatter plots of significant correlations between COP parameters and FOF in sitting

COP: center of pressure; ML: medial-lateral; RMS: root mean square; MPF: mean power frequency.

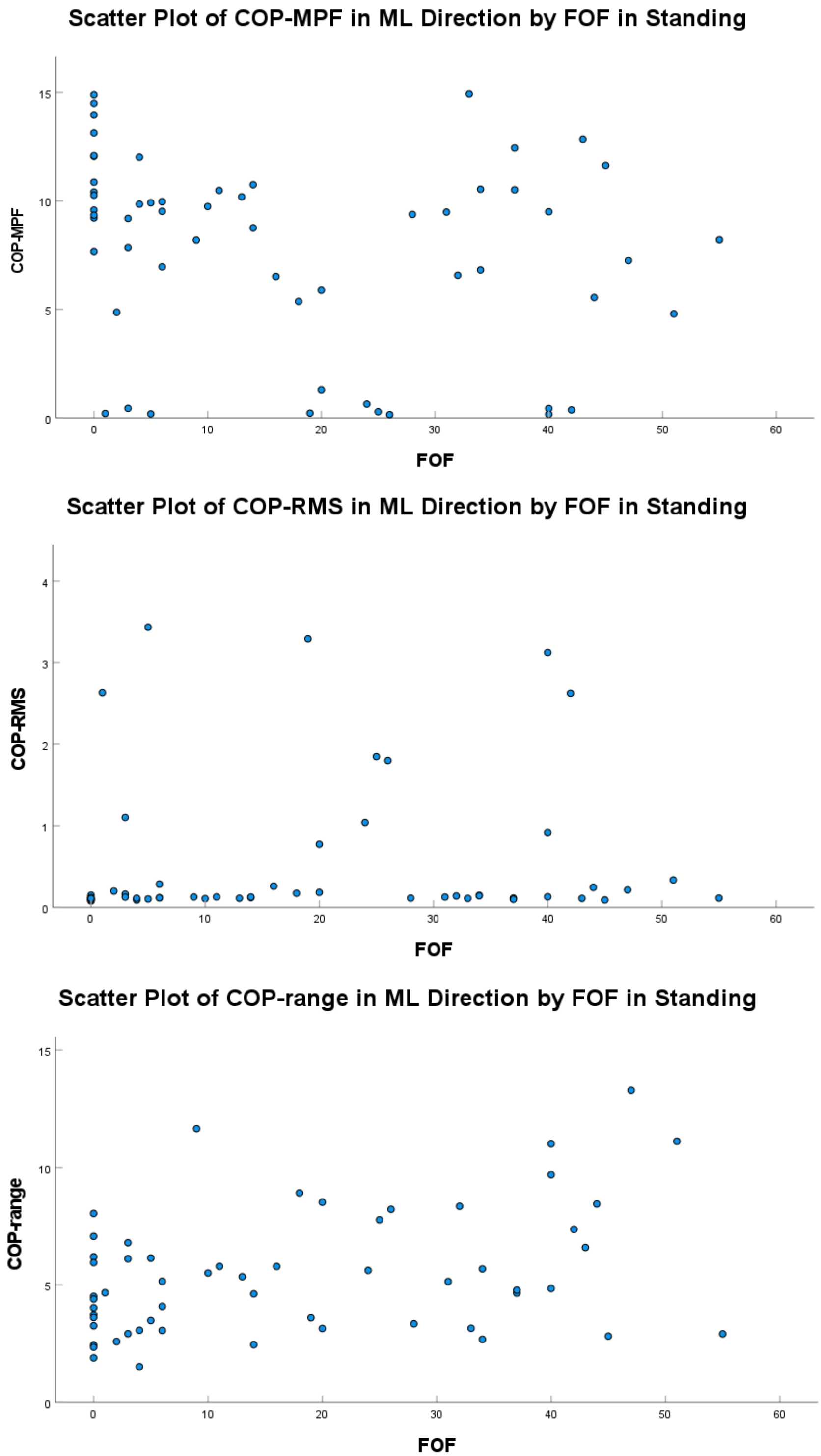

Figure 6: Scatter plots of significant correlations between COP parameters and FOF in standing

COP: center of pressure; ML: medial-lateral; RMS: root mean square; MPF: mean power frequency.

CHAPTER 4: DISCUSSION

Our study explores the practicability of quantifying FOF through objective balance control measures by identifying the appropriated level of FOF, sensitive body sway parameter(s), and the way to compensate for people intolerable to standing. Our results support the first hypothesis that the 360-degree roller coaster videos induced increased FOF compared to the video of the laboratory room. The 360-degree roller coaster videos were able to induce the FOF that were high enough to change the postural control strategies in the healthy young adults during both sitting and standing conditions. However, the second hypothesis was rejected because the change of the body sway frequency and the body sway amplitude were in the opposite direction of our hypothesis. Increased body sway amplitude and decreased body sway frequency were observed in young healthy population with increased FOF during sitting and standing. No muscle activity changes with changed FOF were noted in the current study. Finally, our results partially support the third hypothesis. During standing, FOF correlated to COP-range, COP-MPF, and COP-RMS in ML direction; but FOF only correlated to COP-MPF and COP-RMS in ML direction during sitting.

COP measures

Stiffening strategy of postural adaptation under fearful situations have been consistently observed among studies.[68-70,72] It is considered as a useful strategy to maintain balance by decreasing the possibility of COP moving out of the base of support. We anticipated that subjects in the present study would adopt the same strategy while watching 360-degree roller coaster videos. Surprisingly, body sway parameters changed in the opposite direction of our original hypothesis. Increased amplitude and decreased frequency of COP trajectories were observed with increased level of postural threat and increased FOF.

Increased body sway amplitude under fearful condition was also reported in a study from 2014.[66] People with intolerance to height, a disorder resembling acrophobia but in a less severe extent, demonstrated increased COP range when standing at a height of 15 m compared to ground floor. Davis[75] reported a similar finding in about one third of their study subjects in young adult population. They categorized subjects into "fearful" and "non-fearful" groups based on the change of the FOF reported between standing on ground level and 3.2 m above ground level. Ten out of the 36 subjects in the "fearful group" showed increased body sway amplitude with increased standing height; the remaining 26 subjects who reported little to no FOF change, demonstrated decreased COP-RMS under high condition. One common characteristic of two studies is that subjects who demonstrated increased sway amplitude tended to be under higher level of fear compared to subjects who demonstrated "classic" stiffness strategy. The population with intolerance to height had a greater fear to height compared to the normal population, and the height utilized in that study, 15 m, is much higher than most other studies that investigated the COP change with increased fear. In the second study, the "fearful group" represented the population who demonstrated higher fall-related fear while standing on an elevated surface. The increases of COP-RMS and COP-range with roller coaster videos in the present study indicated that those videos were successful in inducing FOF and altering postural change accordingly. Increased sway range reflects the inability of maintaining the COP in a narrower space and preventing the COP from moving out of the base of support.

Subjects in the present study who did not tighten their COP may demonstrate decreased ability of maintaining the COP away from the balance boundaries. However, it is unclear if increased sway range during standing under fearful situations can reflect the impaired sway control and increased fall risk during standing, even our subjects did not actually lose their balance. Future studies are needed to investigate the effect of increased body sway range during standing. If the increased body sway amplitude is approved to increase the risk of falling, which is consistent with the relationship between FOF and falls. Changed body sway during standing under fearful conditions could be used as an early and safe indicator to predict fear of falling. People, who demonstrate lower ability of maintaining a "safe" body sway control under threatening conditions, will have higher risk of falling.

To our best knowledge, the present study is the first study that reports a negative correlation between sway frequency and FOF. Most studies observed increased sway frequency associated with increased postural threat. Carpenter[73] and Sturnieks[74] revealed unchanged sway frequency under an elevated condition. However, the height of standing surfaces used in the two studies, 0.65m and 0.81m, were relatively low compared to other studies. The unnoticeable change of sway frequency was considered as the evidence of unsuccessful/insufficient disturbance of balance control. Increased sway frequency with increased FOF and decreased sway range are two important elements of stiffness strategy with increased FOF. Sway frequency is a more robust parameter than COP amplitude in the stiffness strategy. Even though the population with intolerance to height standing on 15 m height and the "fearful population" mentioned above failed to reduce the COP amplitude, they still demonstrated increased sway frequency as an attempt to adopt the stiffness strategy. Decrease sway frequency in the present study had even less tendency to adopt the stiffness strategy under fearful conditions. In the present study, people increased their sway amplitude and decreased their sway frequency at the same time. When people cannot keep their COP "tight" inside the base of support, rapid oscillation can bring the COP back to the base of support promptly once the COP is outside of the base of support to prevent the loss of balance. On the contrary, the quicker motion might contribute to shorter reaction time when COP moves out of the boundaries. The present study cannot provide enough information to determine that the decreased sway frequency is beneficial or detrimental to the balance with the increased sway range. Future studies should be performed to explore the influence of this concurrent sway amplitude increase and sway frequency decrease on human balance.

EMG measures

Altered muscle contraction is also associated with postural adjustments. Increased co-contraction of leg muscle contributed to the increase of stiffness of postural control under threatening conditions. Carpenter[73] also found that people activated the anterior leg muscles, inhibited the activation of the posterior leg muscles, and shifted away from the postural threat with increased FOF. However, in the present study, no difference of muscle contractions of Ta, Rec, Gas and Ham were noticed under roller coaster 360-degree video conditions, and muscle activation was not associated to the FOF either. Two reasons might explain the inconsistences. Subjects in our study failed to “tighten” their body sway by increasing COP frequency and decreasing COP amplitude, and the increased co-contraction is a strategy utilized to increase the stiffness of COP control. Failure of “stiffness” could imply the possible underlying failure of the corresponding leg muscle activation pattern and increased co-contraction as well. Different from previous studies, this study introduced a dynamic 360-degree videos to induce visual perturbation in all three directions. Compared to increased standing height, which mostly induced perturbation in AP direction, people in this study might adopt a COP mean position adjustment strategy that is more complex than just leaning backwards. The limitation of our study was that the muscle groups we investigated are primary for joint movement in AP direction. Activation information of the muscle groups of other directions such as hip adductors/hip abductors and ankle muscles of inversion/eversion might provide further information about the muscle contraction with perturbations from multiple directions.

ML and AP comparisons

Posture changes are more sensitive in the direction in which postural threats are present.[68,73,78] In this study, body sway adjustment changes were induced by postural threat in both ML and AP directions. Those changes indicate that 360-degree roller coaster videos used in the present study induced postural threat effectively in both ML and AP directions. Interestingly, the correlation between FOF and postural change were only found in ML direction. Researchers had different speculations about the postural control in AP and ML directions during static standing. Blaszczyk et al[79] revealed a larger proportion of effort allocation in motor control in sagittal plane compared frontal plane. Morrison et al[80] stated that due to less control over the ML direction, postural control in the ML direction is more sensitive to a neuromuscular disease such as multiple sclerosis. In contrast, less sensitivity to visual perturbation was found in the ML direction compared to the AP direction during static standing.[81] O'Connor and his collegue[81] believed that different configurations of human structure explain the less susceptivity to balance perturbation in ML direction. They believed that human body acts like an inverted pendulum in AP direction; and legs, pelvis and ground formed a four-bar linkage in ML direction. The four-bar linkage is more stable during standing and less sensitive to the perturbations compared to the inverted pendulum. Our finding indicated the postural change in ML direction is more sensitive to changed FOF compared to sway change in AP direction. Another finding of the present study consistent with higher sensitivity in the

ML direction was that people demonstrated more FOF with the Pa video than the Ma video. Multiple factors (time of video, speed of roller coaster, etc.) could influence the FOF but current findings partially implied that rotational perturbation induces higher fear than height change. People are more susceptible to visual perturbation in ML direction than in AP direction. More studies needed to investigate the underlying mechanism of the directional sensitivity of postural control in response to FOF and different effectiveness of visual perturbation in ML and AP directions.

Standing and sitting comparisons

The present study is the first study that investigated the relationships between FOF and body sway change in the sitting position. People demonstrated similar postural adaptations in standing and sitting under stressful conditions. During the correlation analysis, both the body sway frequency and amplitude under sitting condition generated higher effect size compared to standing condition (large effect sizes during sitting and moderate effect sizes during standing). This phenomenon might be explained by the complexity of the task. Maintaining balance during sitting is a less demanding task with larger base of support compared to keeping stability during standing. As a result, with the increased postural threat, the strategies utilized during sitting are simpler and the changes are more linear. The linear change is easier to be detected by correlation analysis. We speculated that the greater effect size of the correlation between postural control change and FOF during sitting indicate less variability of the relationship between the FOF and postural control due to less complexity of the task.

One of the purposes of current study is to investigate possible methods to quantify psychological concern, FOF, by using objective parameters of postural control. The benefit of utilizing sitting posture is to decrease the potential influence of impaired balance control during standing. Populations with disorders that can impair balance control have increased risk of reporting FOF. As people age, even without any conditions that might influence balance, the elderly demonstrates increased body sway due to aging process of neuromuscular system. Sitting protocols are safer and more tolerable for the population with increased fall risk. Significant findings during sitting condition provide a possible direction of future investigation of utilizing motor control to quantify FOF for the population that cannot tolerate standing or have safety issues with standing protocols.

Limitations

Besides the limitations mentioned above, the present study has several additional limitations. Convenience sampling method was utilized for the subject recruitment. Most subjects (18 out of 19) were students from the same medical center. The limited heterogeneity of subjects influenced the generalizability of the study findings to all healthy young adults. The relatively small sample size also decreased the generalizability of this study. Also due to the small sample size, dependent variables investigated in the current study demonstrated great standard deviation and failed to achieve the normal distribution. The utilization of the non-parametric statistical analysis decreased the power of the study results and increased the chance of type II error for the parameters that were found to have no significant correlations with FOF. However, current study serves as an important pilot study of quantifying FOF by identifying the objective balance control parameters, exploring the feasibility of the portable devices (e.g. Wii Balance Board), utilizing dynamic virtual conditions to generate FOF, and investigating an alternative way for population that cannot tolerate standing. Studies with a larger sample size should be performed in the future to address those limitations.

Only healthy young adults were recruited in the present study. However, the elderly and people with balance deficits are groups with increased FOF and fall risks.

Even though previous studies indicated that young adults and elderly adults demonstrates similar balance control strategies under fearful conditions, this may not be the case with current study setting. Because 360-degree videos in the present studies induced higher FOF and elicited different motor control strategies compared to previous studies that used elevated standing height. Results of the present study cannot be generalized to the elderly population and people with balance impairments. Future studies should be performed to investigate the postural control strategies of those populations with dynamic 360-degree videos.

The current study aimed to quantify FOF. However, only situational FOF (FOF with the 360-degree video) was included. The relationship between postural changes under fearful situations in standing and other constructs of FOF (e.g., falls efficacy and balance confidence) were not assessed. Also, because we used roller coaster videos in the current study, we should be cautious about extrapolating our study results to FOF from other activities like walking crossing the street, walking on different surfaces, etc. Another limitation of the current study is about the dynamic nature of the 360-degree videos we utilized. Although we utilized dynamic videos to induce FOF; the dynamic video itself might influence the body sway. However, dynamic 360-degree videos increase the external validity of our study because people usually report FOF about dynamic movements, especially higher functional activities.

Future studies should assess the relationships between situational FOF and other subjective measurements, and the associations between changed postural control and other subjective scales (e.g., FES and SAFFE) to explore the practicability of quantifying FOF by using objective kinetic and kinematic parameters. Previous studies found that the relationship between postural control during standing and psychological concern of falls changed with the intensity of the FOF change.[75] Current study was able to generate significant change of FOF. However, 38.2% of trials under roller coaster conditions induced none to low FOF (⩽10/100) in the current study. The current study did not perform analysis based on the level of FOF, which might influence the results by mixing the different strategies based on the different levels of FOF. The appropriate cut off of the FOF is currently unknown. More studies are needed to identify the relationships between FOF and postural control under fearful situations based on the levels of reported FOF.

Conclusions

To our knowledge, the present study is the first study to explore how to quantify FOF by utilizing objective kinetic and kinematic parameters. And this is also the first study that tried to induce FOF by utilizing dynamic 360-degree videos of roller coasters. Those videos were successful in eliciting psychological fear about falling and changed postural control during standing in young healthy adults. Although postural control strategies in the current study cannot be explained by the classic ”stiffing strategy”, COP-MPF and COP-RMS in ML direction during sitting as well as COP-range, COP-MPF, and COP-RMS in ML direction during standing are sensitive parameters to quantify FOF with 360-degree videos. More studies are needed to investigate the applicability of this method in different populations and for different constructs of FOF.

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