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Balancing on the Edge: Review and Computational Framework on the Dynamics of Fear of Falling and Fear of Heights in Postural Control

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Abstract

This review explores the complex relationship between Fear of Falling (FoF) and Fear of Heights (FoH), and their impact on human postural control. FoF encompasses a spectrum of psychological and physiological responses that dynamically influence postural control, while FoH involves perceptual distortions and heightened physiological arousal in response to elevated environments. Through a comprehensive literature review, we examine the research methods and findings of studies on FoF and FoH. We further propose that Optimal Feedback Control (OFC) theory is a suitable framework to understand the computational aspects of how these fears modify postural control. We aim to provide a nuanced understanding of FoF and FoH, not only as psychological phenomena but as complex, dynamic interactions of cognitive, physiological, and motor processes influencing an individual's interaction with their environment.

Keywords: Fear of Falling; Fear of Heights; Balance Control; Postural Sway; Optimal Feedback Control

Introduction

Postural control, crucial for maintaining balance, is significantly influenced by psychological factors such as fear. (Adkin, Frank, Carpenter, & Peysar, 2000). Fear, a primal emotion, plays a critical role in human survival by initiating the 'fight or flight' response to threats (Misslin, 2003).

Fear, more than a psychological state, continuously interacts with and impacts motor control systems. Specifically, Fear of Falling (FoF) and Fear of Heights (FoH) have been found to alter motor control strategies, leading to changes in gait, posture, and balance (Adkin, Frank, Carpenter, & Peysar, 2002; Ellmers, Maslivec, & Young, 2020; Wuehr et al., 2014). These effects potentially stem from a complex interplay between cognitive and physical dynamics, which we posit in Figure 1. The cognitive dynamics involve the perception of postural threat in the form of exposure to heights or external disturbances, the emotional response to this threat in the form of fear, and the modification of balance control goals based on the emotional response, while the physical dynamics involve the physical control of balance and the resulting postural sway, which can also affect the fear response.

This paper explores how FoF and FoH influence cognitive processes affecting postural balance. We first present a literature review on FoF and FoH effects, focusing on key research methodologies and findings related to postural balance. Then, we propose a theoretical explanation for the differential effects these fears have been found to have on postural sway through the lens of optimal feedback control (OFC) theory.

Fear of Falling

FoF, common in the elderly, involves cognitive, physiological, and behavioral concerns about falling. It can be influenced by factors such as prior experiences of falling and age-related concerns (Arfken, Lach, Birge, & Miller, 1994). FoF can occur even without a history of falls and is often linked to balance disorders (Vellas, Wayne, Romero, Baumgartner, & Garry, 1997). FoF in individuals with fall history leads to reduced physical activity and motor performance (Park, Atique, Mishra, & Najafi, 2022), impacting balance confidence and increasing health concerns (Ponzano et al., 2020), perceived fall risk (Tinetti, Richman, & Powell, 1990), and actual fall incidents (Legters, 2002).

Research Methods

FoF studies often include environmental manipulations and assessments of postural stability and physiological and psychological responses.

Experimental Manipulations Maki, Holliday, and Topper (1991) developed a method to assess balance performance, which included analyzing spontaneous sway, inducing anterior-posterior (AP) and medial-lateral (ML) sway to examine responses to directional challenges, and one-leg stance for testing unilateral postural control. In general, methods to induce FoF can include mechanical disturbances, exposure to real heights, simulated heights, and psychological pressure (Geh, Beauchamp, Crocker, & Carpenter, 2011). For this review, we narrow our scope to manipulations involving real or simulated heights, to facilitate comparison with FoH manipulations. Exposure to real heights up to 3.2 meters above ground has been realized using hydraulic platforms to switch between exposure conditions (Adkin et al., 2000; Brown, Polych, & Doan, 2006; Davis, Campbell, Adkin, & Carpenter, 2009; Horslen, Murnaghan, Inglis, Chua, & Carpenter, 2013), or an elevated, narrow walkway (Osler, Tersteeg, Reynolds, & Loram, 2013). Additionally, exposure to simulated heights of comparable magnitude in virtual reality setups has been found to elicit FoF and its typical postural responses (Cleworth, Horslen, & Carpenter, 2012).

Posturographic Measures Postural sway is a crucial parameter in assessing balance and stability and can be understood as excursions of the center of pressure (CoP). Analyses

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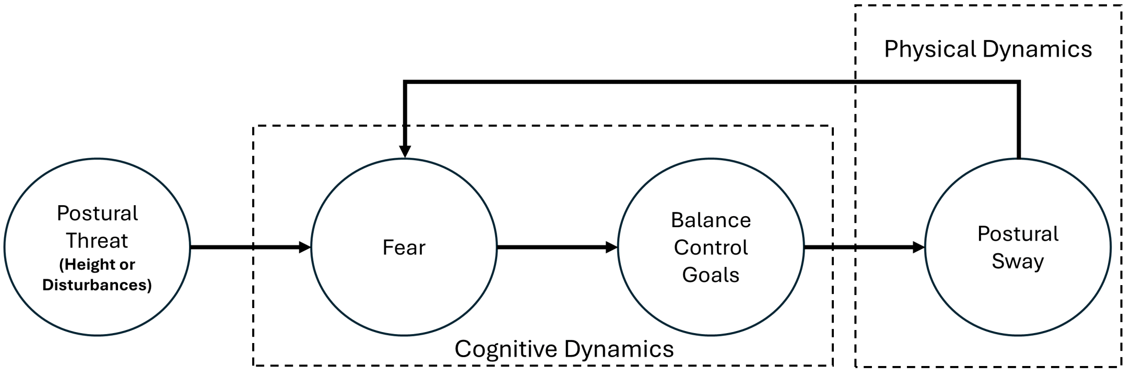

Figure 1: The postural effects, such as sway, induced by postural threat demonstrate an interplay of cognitive and physical dynamics. Cognitive dynamics includes perceiving postural threat (e.g., heights, disturbances), responding emotionally with fear which leads to changes in balance control goals; physical dynamics entail the physical balance control and resulting postural sway, which can also affect the fear response.

of postural control reactions typically involve the investigation of the CoP mean, standard deviation and mean power frequency (MPF) (Adkin et al., 2000; Carpenter, Frank, Silcher, & Peysar, 2001; Brown et al., 2006; Zaback, Luu, Adkin, & Carpenter, 2021) as well as root-mean-square (RMS) (Davis et al., 2009; Cleworth et al., 2012; Zaback, Adkin, & Carpenter, 2019), range (Brown et al., 2006), and shift ability (Binda, Culham, & Brouwer, 2003). Standing on force plates (Carpenter et al., 2001; Davis et al., 2009) provides real-time, precise measurements of the body's responses to balance disturbances.

Physiological Measures Physiological measures typically used in the studies on FoF involve electromyography (EMG) and electrodermal activity (EDA) assessments. EMG is extensively used to asses muscle activity, particularly in the tibialis anterior, medial head of gastrocnemius, and soleus, offering insights into how these muscles coordinate and adapt during fear-induced postural control (Okada, Hirakawa, Takada, & Kinoshita, 2001; Horslen et al., 2013; Wuehr et al., 2014; Nagai et al., 2012). EMG assessments are also used to calculate the co-contraction index (CCI) to measure the simultaneous activation of agonist and antagonist muscles. CCI is particularly relevant in understanding the strategies employed by the nervous system to stabilize the body under challenging conditions. EDA is used to measure the physiological arousal during exposure to postural threats (Davis et al., 2009, 2011; Horslen et al., 2013; Horslen, Dakin, Inglis, Blouin, & Carpenter, 2014; Horslen, Inglis, Blouin, & Carpenter, 2017).

Cognitive-Psychological Measures To examine the subjective and cognitive aspects of FoF, various psychological measures have been conducted. Instruments such as the Falls Efficacy Scale (Chamberlin, Fulwider, Sanders, & Medeiros, 2005; Nagai et al., 2012) or Self Perceptions of Balance (Brown et al., 2006) are employed to quantify individuals' confidence in their ability to maintain balance and prevent falls. These scales provide insights into the personal apprehensions and concerns related to falling. Self-reported measures also extend to evaluating perceived state anxiety, a reflection of the individual's emotional response to balance-related challenges or heights. For measuring perceived anxiety, several studies (Davis et al., 2009, 2011; Horslen et al., 2013) have used the questionnaire from (Adkin et al., 2002) which has been demonstrated to have moderate to high reliability (Hauck, Carpenter, & Frank, 2008). Perceived stability, another subjective measure, indicates the individual's sense of balance and security, especially when positioned at heights or during balance tasks (Davis et al., 2011).

Effects on Postural Balance

FoF is associated with postural control, reducing performance in balance tests like spontaneous sway and one-leg stance, often more significantly than the history of falls themselves Maki et al. (1991). Binda et al. (2003) found strong correlations between FoF, balance ability, and muscle strength. Those with greater fear exhibited lesser AP sway and limited maximal weight-shifting ability. Importantly, the response in postural control is scaled to the level of perceived postural threat (Adkin et al., 2000). Increases in perceived postural threat lead to a posterior shift in the mean AP position of CoP, a decrease in CoP sway amplitude, and an increase in CoP mean power frequency (MPF) (see Table 1). Perceived postural threat also leads to a posterior shift in the center of mass (CoM) and an increase in CoP MPF for the ML direction (Cleworth et al., 2012). Adkin et al. (2000) found that the impact of prior exposure to postural threats is evident in the modulation of postural control strategies. In their study, participants exposed to high-threat conditions as first test condition showed greater amplitude of CoP displacement in the AP direction across all postural threat conditions compared to those first exposed to a low-threat condition. The decreased sway amplitude and increased sway frequency, as well as heightened perceptions of FoF after fear priming can be observed across different age groups (Brown et al., 2006; Stamenkovic, van der Veen, & Thomas, 2020). Stamenkovic et al. (2020) further found that older participants showed a reduction in total ML CoM excursion with shorter and wider steps. In the study conducted by Okada et al. (2001), abrupt deceleration of a moving platform led to higher response times and CoP displacements, as well as a higher level of co-contraction in their lower extremity muscles in elderly women with compared to without FoF. This increased co-contraction likewise can be observed during walking (Nagai et al., 2012). Increased activity in anterior muscles (tibialis anterior) and decreased activity in posterior muscles (soleus) is observed together with an increased stiffening, independent of vision or vestibular information (Carpenter et al., 2001). Postural threat due to height exposure and balance disturbances, respectively, has been found to increase stretch (T)-reflex amplitude in the soleus muscle without any significant change in Hoffmann-reflex amplitude or background EMG (Horslen et al., 2013), pointing to increased muscle-spindle sensitivity. The authors suggest that these findings reflect conflicting goals to restrict movement while maintaining a certain amount of sensory information related to postural control.

In addition to postural balance, FoF also affects gait in multiple ways. FoF not only slows gait velocity in older adults (Reelick, van Iersel, Kessels, & Rikkert, 2009) but also impacts their walking patterns, as seen in shorter strides, wider stances, and prolonged support phases (Chamberlin et al., 2005). These individuals also exhibit greater stride time variability and poorer trunk movement coordination (Sawa et al., 2014). Moreover, FoF influences gait initiation, prompting a "freezing" response, delayed and diminished anticipatory postural adjustments, and shorter initial steps, which may heighten the risk of falls (Ellmers et al., 2020). These findings collectively underscore the profound, multifaceted impact of FoF on postural control.

Fear of Heights

FoH is characterized by an irrational and excessive fear when at significant elevation or even in anticipation of it. FoH involves visual perception and impacts postural balance. It is a complex condition that can significantly impact an individual's functioning and quality of life.

Characterization and Perceptual Biases

People with FoH tend to show attentional biases and a misinterpretation of bodily symptoms. Visual field-dependence, poor non-visual postural control, and high sensitivity to bodily symptoms can increase the likelihood of developing FoH (Coelho & Wallis, 2010). Further, people with FoH often avoid a wide range of stimuli, such as climbing ladders or getting close to windows in high-rise buildings, indicating that their fear can be triggered even in situations with minimal risk of falling or getting injured (Wiederhold & Bouchard, 2014). For example, Krupić, Žuro, and Corr (2021) showed that individuals with acrophobia experienced increased subjective levels of distress when exposed to heights in a controlled and safe environment using virtual reality.

Teachman, Stefanucci, Clerkin, Cody, and Proffitt (2008) found that individuals with high FoH perceived balconies to be higher than they actually were, suggesting a perceptual bias influenced by their fear. This perceptual bias influences the decision-making and behavior of individuals with FoH, leading to unnecessary caution or avoidance. Clerkin, Cody, Stefanucci, Proffitt, and Teachman (2009) revealed that individuals with greater FoH tend to overestimate the vertical extent of heights more significantly when they imagine themselves falling, suggesting a direct link between fear and perceptual distortion. This overestimation was found to be more pronounced in individuals with a preexisting FoH, indicating that such fear may serve as a vulnerability factor leading to greater perceptual biases when triggered by stressors like the imagery of falling.

In general, humans are inherently more sensitive to vertical heights than to horizontal distances, and this sensitivity is exacerbated by higher levels of trait and state anxiety, contributing to FoH (Staab, 2014). Further, FoH, particularly as a stable trait, can exaggerate perceived heights and affect actions like stepping over gaps. Although fear influences both perception and actions, there is a dissociation between how fear alters perceptions and actual actions performed. This finding underlines the dual impact of fear on both perception and interaction with the environment (Geuss, McCardell, & Stefanucci, 2016).

Research Methods

Studies on FoH typically involve the same posturographic, physiological, and cognitive-psychological measures as those on FoF. The primary difference lies in the experimental manipulations. While FoF studies use raised platforms up to heights of 3.2m, studies on FoH use exposure to heights above 15m. Some studies have used real-world settings, such as standing on a balcony (Wuehr et al., 2014) or an elevated platform in a theme park (Alpers & Adolph, 2008). Some other studies have used virtual reality environments to conduct experimental investigations that might not be feasible in real-world settings, such as standing on an unprotected platform at heights up to 40m (Bzdúšková, Marko, Hirjaková, Riečanský, & Kimijanová, 2023), walking on a hanging plank on an 80-stories high skyscraper (Krupić et al., 2021) or standing on a semi-circular platform on the exterior of a tall building at heights up to 100m (Wuehr et al., 2019). Hüweler, Kandil, Alpers, and Gerlach (2009) used visual flow stimuli through Head-Mounted Displays (HMD) to expose individuals to conflicting visual and somatosensory information. This method is particularly effective in studying how sensory conflicts contribute to the FoH, providing insights into the perceptual-cognitive aspects of acrophobia. Measures like visual matching tasks (Clerkin et al., 2009) have been used to minimize cognitive biases and more directly investigate perceptual biases. These tasks assess how individuals perceive their environment, particularly when height and depth cues are involved.

Cognitive and Sensorimotor Dynamics

Several studies have explored the relationship between FoH, visual exploration and postural control. Kugler, Huppert, Schneider, and Brandt (2014) investigated the influence of FoH on visual exploration behavior. They found that individuals with FoH showed limited eye and head movements and focused their gaze straight ahead, particularly on the horizon, when facing heights. This behavior, likely a coping mechanism to reduce anxiety, could impair balance control and danger assessment in high places. The study indicates that training in visual exploration might help manage FoH-related anxiety and balance issues. Hüweler et al. (2009) discovered that FoH increases individuals' sensitivity to visual flow stimuli, leading to increased anxiety, dizziness, and body sway, especially when visual and somatosensory information is incongruent. Their findings indicated an over-dependence on visual information for balance in individuals with FoH, as evidenced by elevated CoP velocity, particularly in conditions with vertical oscillations. Alpers and Adolph (2008) observed that exposure to heights exacerbates body sway, intensifying further when individuals close their eyes. These observations suggest that the awareness of being at a height amplifies sway. Notably, anticipated fear was a consistent predictor of experienced fear and sway during height exposure, with the study underscoring anticipatory fear and subsequent avoidance behaviors as responses to physiological and emotional distress symptoms like discomfort, dizziness, and palpitations experienced at heights. Wuehr et al. (2014) examined the impact of visual height intolerance on postural control. The study found that exposure to heights disrupts open-loop control, making it less effective. It also sensitizes closed-loop control, as indicated by higher diffusion activity and a lowered sensory feedback threshold. These changes in postural control, often coupled with increased muscle co-contraction in anti-gravity muscles, were directly linked to the severity of anxiety induced by heights, highlighting the profound effect of visual heights on both postural strategy and muscular response.

Computational Perspective

FoF and FoH, while similar, distinctly influence postural balance. As we summarize in Table 1, both fears increase CoP oscillation frequencies, yet FoF typically reduces CoP oscillation amplitudes in response to postural threats, in contrast to the amplification observed with FoH. We adopt a computational approach, graphically represented in Figure 1, particularly through the lens of OFC theory, to provide possible explanations for these contrasting findings.

Computational Perspective on Fear of Falling

FoF deviates from predicted stability (Clark, 2013), stemming from the brain's integration of sensory inputs to model body-state interactions (Mergner & Rosemeier, 1998). When this integration signals a discrepancy between the current state and the desired safe state of balance, such as a potential fall, it is perceived as a threat (Horak, 2006). This discrepancy elicits a fear response as an attempt to minimize the prediction error in the brain's model, leading to an updating of its predictions and altering of motor commands, aimed at regaining balance and safety. Recalibrating motor commands to prioritize safety can manifest as anticipatory adjustments like overly cautious movements with reduced gait velocity or a wider stance (Chamberlin et al., 2005; Reelick et al., 2009) or reactive responses like grabbing onto external supports upon losing balance (Maki & McIlroy, 1996). The brain adapts its motor control algorithms to lower the perceived falling risk, often compromising movement efficiency.

The typically observed stiffening response and cautious gait can be seen as a response to fear-induced alterations in attentional control and processing efficiency, leading to freezing. Individuals with FoF tend to rely more on visual cues, often leading to gaze diversion and potential balance disturbances (Young & Williams, 2015). This overreliance, stemming from increased vigilance and anticipation of threats, may lead to an overestimation of fall likelihood or severity, heightening anxiety and fear. Computationally, this can be linked to an algorithm overweighting the probability of negative outcomes, leading to disproportionate avoidance behavior (Wolpert & Miall, 1996). On a longer timescale, individuals consequently might decrease physical activity, further exacerbating balance issues. Importantly, the reduced balance confidence in FoF increases fear and creates a self-reinforcing feedback loop where increased fear exacerbates cautious behavior, further diminishing balance ability and confidence (Binda et al., 2003; Davis et al., 2011; Horslen et al., 2013).

Computational Perspective on Fear of Heights

As with FoF, FoH reflects a deviation from a perceived safe state. Significant heights induce a fear response due to the stark contrast between the expected safe state on one hand, and visual and vestibular cues on the other, signaling a high fall risk (Boffino et al., 2009). The fear response aims to minimize the prediction error, often manifesting as a strong urge to avoid edges or high places. FoH also involves a distortion in cognitive algorithms processing sensory information, predicting threats, and preparing the body for appropriate motor responses (Coelho & Wallis, 2010). In FoH, the brain's world model, heavily influenced by fear-based hypotheses rather than actual sensory data, leads to exaggerated height perceptions and risk assessments (Teachman et al., 2008). Attentional biases in FoH cause a disproportionate focus on height-related cues, neglecting other sensory inputs that could mitigate perceived risks (Coelho & Wallis, 2010). These biases reflect a computational misallocation, overly concentrating on threat-related stimuli.

Table 1: Effects of height-induced postural threat on CoP sway in Anterior-Posterior (AP) direction.

Paper	Height Levels*	Amplitude	MPF	Mean
Adkin et al. (2000)	0.4 m, 1m, 1.6m (R)	Decreased	Increased	Posterior shift
Carpenter et al. (2001)	0.19m, 0.81m (R)	Decreased	Increased	Posterior shift
Brown et al. (2006)	0.17m, 1.4m (R)	Decreased	Increased	Posterior shift
Davis et al. (2009)	0m, 0.8m, 1.6m, 3.2m (R)	Increased (Fearful), Decreased (Non-fearful)	Increased	Posterior shift
Davis et al. (2011)	0.8m, 3.2m (R)	Decreased	Increased	Posterior shift
Cleworth et al. (2012)	0.8m, 3.2m (VR/R)	Decreased	Increased	Posterior shift
Zaback et al. (2019)	0.8m, 3.2m (R)	Decreased	Increased	Posterior shift
Zaback et al. (2021)	0.8m, 3.2m (R)	-	Increased	Posterior shift
Alpers and Adolph (2008)	0m, 16m (R, FoH)	Increased	Increased	-
Wuehr et al. (2014)	0m, 15m (R, FoH)	Increased	-	-
Wuehr et al. (2019)	0m to 100m (VR, FoH)	Increased	-	-
Bzdúšková et al. (2023)	0m, 40m (VR, FoH)	Decreased	-	No shift (Low fear), Posterior shift (High fear)

*R: Real-world setting; VR: Virtual-reality setting; we categorize studies that used heights above 15m as FoH studies.

OFC Theory in Postural Control and Adaptation

The nuanced effects of fear on postural balance, particularly the contrasting findings related to the CoP amplitude in studies of FoF versus FoH, present a complex picture. We propose that these findings depend on the intensity of the fear-inducing stimulus and that OFC theory can provide explanations for these findings.

OFC theory (Todorov & Jordan, 2002) views the nervous system as a predictive controller constantly making predictions about the future based on sensory inputs and internal models, striving to minimize a cost function related to movement. The perceptual input (e.g., the depth when standing at the edge of a platform) can be modeled as a sensory signal that is integrated into the CNS's internal representation of the current state. The discrepancy between this perceived state and the desired safe state (prediction error) can be quantified. This prediction error is typically penalized by the cost function and motor commands are adjusted to minimize it. Additionally, motor commands themselves are typically penalized either explicitly, e.g. by a cost term for energy expenditure, or implicitly by control noise scaling excessively with larger commands (e.g. due to neural transmission noise). As such, OFC control output reflects a trade-off between minimizing both, prediction errors, and control actions (minimum intervention principle). We posit that differential findings on the effects of FoF and FoH on balance may be explained by their differential effects on this trade-off.

OFC in FoF While studies on FoF often indicate a decrease in CoP amplitude, suggesting a more stable yet rigid postural control, investigations on the impact of FoH typically report an increase in CoP amplitude, denoting greater instability. These seemingly contradictory responses can be explained by OFC theory which posits that the motor system's response to fear involves a complex interplay between control effort, motor noise, and adaptive strategies employed by the nervous system. Studies on FoF typically use postural threat paradigms where participants are exposed to heights of a maximum of 3.2 meters. The associated postural threat, while significant, is not perceived as life-threatening. OFC theory suggests that in such situations, the nervous system prioritizes maintaining balance with a controlled, cautious approach. In this case, exerting a higher amount of control results in a decrease in CoP amplitude, reflecting a stiff but stable posture, a natural reaction where muscle tension increases to brace the body against potential loss of balance (Winter, 1995). The nervous system, in this case, appears to optimize for energy conservation and minimization of movement, a strategy that reduces the likelihood of a fall.

OFC in FoH Studies on FoH, on the other hand, typically use elevations of 15 meters and above (Alpers & Adolph, 2008; Bzdúšková et al., 2023; Wuehr et al., 2014), which represents a more life-threatening scenario in case of a fall. The intense fear response to greater heights is an evolutionary mechanism reflecting the life-threatening nature of high-altitude falls (Rachman, 2004). The nervous system might respond to this intense fear by significantly increasing control effort to secure stability in a high-risk situation. However, this may paradoxically lead to a reduction of stability. A key prediction of OFC is the 'minimum intervention principle' (Todorov & Jordan, 2002): if the controller is noisy, increased control effort will also increase motor output noise. Hence, the controller should be used as little as possible, to maximize the probability of reaching the control goal, here: a stable posture.

Thus, in its attempt to minimize the risk of a catastrophic fall, the nervous system, inadvertently increases postural sway due to the signal-dependent nature of motor noise. Motor noise is inherently tied to the control signals, with the intensity of control effort proportionally influencing the motor noise. In summary, the typical stiffening response in face of postural threats may reflect an attempt at heightened control over body movements to counteract the perceived threat through enhanced stability. However, due to the resulting control-dependent motor noise, the associated sway amplitude appears to vary based on the intensity of fear and the height involved. The increased motor noise, as a consequence of the stiffening response, leads to more motor variability. This variability can manifest as increased sway amplitude in situations of intense fear as in the FoH, while in scenarios of moderate fear as in the FoF, the system manages to maintain a controlled stability with decreased sway amplitude.

The Influence of Anxiety

As previously highlighted, research findings on FoF are varied. Generally, studies indicate that individuals with FoF exhibit a decrease in the amplitude of CoP sway. Contrarily, in the study by Davis et al. (2009), where threat-induced postural responses were examined, participants with FoF showed an increase in CoP amplitude, while those without FoF showed a decrease. Notably, both groups experienced state anxiety. This suggests that anxiety contributes to high prediction uncertainty (Grupe & Nitschke, 2013). Such uncertainty often leads individuals to reduce their sway amplitude, adopting a cautious and controlled posture to stabilize balance. However, although this posture aims to enhance stability, it may decrease adaptability to sudden perturbations, thus increasing the risk of instability during unexpected disturbances (Carpenter et al., 2001). Consequently, individuals with a general experience of FoF may adopt a cautious and rigid posture, which, while reducing the likelihood of falls under normal conditions, could impair their response to significant, unexpected disturbances.

In the context of FoH, Wuehr et al. (2019) found that both acrophobic and non-acrophobic participants' subjective fear ratings increased with height, but at a higher rate in acrophobic participants, influencing sway amplitude. This aligns with findings from other studies (Alpers & Adolph, 2008; Hüweler et al., 2009; Wuehr et al., 2014, 2019), suggesting that the heightened anxiety responses to intense stimuli and perceptual biases can lead to an increase in sway amplitude. The intense, immediate reactions often enhance control efforts, inadvertently destabilizing postural balance, as reflected by increased CoP amplitude. Such findings underscore the complex influence of anxiety on motor control and balance, highlighting the need for further investigation into how both anticipatory and reactive aspects of anxiety affect postural stability.

Interpretations and Implications of OFC theory

OFC can help model how individuals with a FoF or FoH might adopt different control strategies based on their perceived risks and costs. For example, individuals with both fears might prioritize minimizing the risk of a fall (increasing the cost of falling in the cost function) leading to a stiff and cautious control policy. But in face of significant postural threat as FoH scenarios, individuals might experience an intense emotional response that heavily weighs the cost of instability, leading to the exertion of too much control, paradoxically leading to a control policy that results in high CoP amplitude and instability likely due to the signal-dependent motor noise. Empirical findings from studies on FoH and FoF can be used to validate and refine the models built on OFC theory. These findings can provide real-world data on how individuals' CoP dynamics change in response to fear, which can then be used to adjust the parameters of the OFC model, making it more accurate and predictive.

We propose that stability is maximized by a precise, optimal level of control force. Excessive control, manifesting as stiffening, may paradoxically lead to increased motor noise and resultant instability. OFC theory can be instrumental in identifying the 'optimal' amount of control force that maximizes stability without introducing excessive motor noise or energy costs.

Suggestions for Future Research

Future studies can integrate computational modeling techniques with empirical experimental data. This enables exploring the predictions of OFC theory by investigating its model parameters in the context of the effects of FoF and FoH on postural control. Examining and testing the specific parameters of the OFC model, such as control effort, motor noise, and the weighting of predictive and sensory feedback, could yield profound insights into the cognitive and physical dynamics governing postural control under the influence of fear. By methodically examining how these parameters fluctuate in response to FoF and FoH, researchers can not only test and validate the predictive power of OFC theory but also elucidate the dynamic interplay between fear, sensory integration, and motor output. A promising approach is to infer the control goals from observable motor output. This might be useful in determining whether our explanations for the different control strategies in FoH and FoF are appropriate. This line of inquiry holds the potential to significantly advance our understanding of fear-induced balance alterations and contribute to the development of targeted strategies to enhance postural stability and motor function in fear-affected populations.

Conclusion

This review advances understanding of FoF and FoH, exploring their distinct effects on postural control through OFC theory. It emphasizes the physiological and psychological mechanisms at play by presenting a comprehensive overview of empirical evidence. This work sets a foundation for future research and targeted intervention strategies, aiming to mitigate the profound effects of these fears on individuals' postural stability and overall well-being.

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References

Adkin, A. L., Frank, J. S., Carpenter, M. G., & Peysar, G. W. (2000). Postural control is scaled to level of postural threat. *Gait & posture*, *12*(2), 87–93.

Adkin, A. L., Frank, J. S., Carpenter, M. G., & Peysar, G. W. (2002). Fear of falling modifies anticipatory postural control. *Experimental Brain Research*, *143*, 160-170.

Alpers, G., & Adolph, D. (2008, May). Exposure to heights in a theme park: fear, dizziness, and body sway. *J Anxiety Disord.*, *22(4)*, 591-601. doi: 10.1016/j.janxdis.2007.05.008

Arfken, C. L., Lach, H. W., Birge, S. J., & Miller, J. P. (1994, Apr). The prevalence and correlates of fear of falling in elderly persons living in the community. *Am J Public Health*, *84*(4), 565–570.

Binda, S. M., Culham, E. G., & Brouwer, B. (2003). Balance, muscle strength, and fear of falling in older adults. *Experimental aging research*, *29*(2), 205–219.

Boffino, C., Cardoso de Sá, C., Gorenstein, C., Brown, R., Basile, L., & Ramos, R. (2009, Mar). Fear of heights : cognitive performance and postural control. *Eur Arch Psychiatry Clin Neurosci.*, *259(2)*, 114-9. doi: 10.1007/s00406-008-0843-6

Brown, L. A., Polych, M. A., & Doan, J. B. (2006). The effect of anxiety on the regulation of upright standing among younger and older adults. *Gait & posture*, *24*(4), 397–405.

Bzdúšková, D., Marko, M., Hirjaková, Z., Riečanský, I., & Kimijanová, J. (2023, Sep). Fear of heights shapes postural responses to vibration-induced balance pertubation at virtual height. *Hum. Neurosci.*, *17*. doi: 10.3389/fnhum.2023.1229484

Carpenter, M. G., Frank, J. S., Silcher, C. P., & Peysar, G. W. (2001). The influence of postural threat on the control of upright stance. *Experimental brain research*, *138*, 210–218.

Chamberlin, M. E., Fulwider, B. D., Sanders, S. L., & Medeiros, J. M. (2005). Does fear of falling influence spatial and temporal gait parameters in elderly persons beyond changes associated with normal aging? *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *60*(9), 1163–1167.

Clark, A. (2013, Jun). Whatever next? predictive brains, situated agents, adn the future of cognitive science. *Behav Brain Sci.*, *36(3)*, 181-204. doi: 10.1017/S0140525X12000477

Clerkin, E. M., Cody, M. W., Stefanucci, J. K., Proffitt, D. R., & Teachman, B. A. (2009). Imagery and fear influence height perception. *Journal of anxiety disorders*, *23*(3), 381–386.

Cleworth, T. W., Horslen, B. C., & Carpenter, M. G. (2012). Influence of real and virtual heights on standing balance. *Gait & Posture*, *36*(2), 172-176.

Coelho, C., & Wallis, G. (2010, Aug). Deconstructing acrophobia: physiological and psychological precursors to developing a fear of heights. *Depression and Anxiety*, *27(9)*, 864-870. doi: https://doi.org/10.1002/da.20698

Davis, J. R., Campbell, A. D., Adkin, A. L., & Carpenter, M. G. (2009). The relationship between fear of falling and human postural control. *Gait & Posture*, *29*(2), 275-279.

Davis, J. R., Horslen, B. C., Nishikawa, K., Fukushima, K., Chua, R., Inglis, J. T., & Carpenter, M. G. (2011). Human proprioceptive adaptations during states of height-induced fear and anxiety. *Journal of Neurophysiology*, *106*(6), 3082-3090.

Ellmers, T. J., Maslivec, A., & Young, W. R. (2020, Jul). Fear of falling alters anticipatory postural control during cued gait initiation. *Neuroscience*, *438*, 41–49.

Geh, C. L., Beauchamp, M. R., Crocker, P. R., & Carpenter, M. G. (2011). Assessed and distressed: White-coat effects on clinical balance performance. *Journal of Psychosomatic Research*, *70*(1), 45-51.

Geuss, M. N., McCardell, M. J., & Stefanucci, J. K. (2016). Fear similarly alters perceptual estimates of and actions over gaps. *PLoS one*, *11*(7), e0158610.

Grupe, D., & Nitschke, J. (2013, Jun). Uncertainty and anticipation in anxiety: an integrated neurobiological and psychological perspective. *Nature Reviews Neuroscience*, *14*, 488-501. doi: https://doi.org/10.1038/nrn3524

Hauck, L. J., Carpenter, M. G., & Frank, J. S. (2008). Task-specific measures of balance efficacy, anxiety, and stability and their relationship to clinical balance performance. *Gait & posture*, *27*(4), 676–682.

Horak, F. (2006, Sep). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age Ageing*, *35 Suppl.2*, ii7-ii11. doi: 10.1093/ageing/afl077

Horslen, B. C., Dakin, C. J., Inglis, J. T., Blouin, J.-S., & Carpenter, M. G. (2014). Modulation of human vestibular reflexes with increased postural threat. *The Journal of Physiology*, *592*(16), 3671-3685.

Horslen, B. C., Inglis, J. T., Blouin, J.-S., & Carpenter, M. G. (2017). Both standing and postural threat decrease achilles' tendon reflex inhibition from tendon electrical stimulation. *The Journal of Physiology*, *595*(13), 4493-4506.

Horslen, B. C., Murnaghan, C. D., Inglis, J. T., Chua, R., & Carpenter, M. G. (2013). Effects of postural threat on spinal stretch reflexes: evidence for increased muscle spindle sensitivity? *Journal of neurophysiology*, *110 4*, 899-906.

Hüweler, R., Kandil, F. I., Alpers, G. W., & Gerlach, A. L. (2009). The impact of visual flow stimulation on anxiety, dizziness, and body sway in individuals with and without fear of heights. *Behaviour Research and Therapy*, *47*(4), 345–352.

Krupić, D., Žuro, B., & Corr, P. J. (2021). Anxiety and threat magnification in subjective and physiological responses of fear of heights induced by virtual reality. *Personality and Individual Differences*, *169*, 109720.

Kugler, G., Huppert, D., Schneider, E., & Brandt, T. (2014). Fear of heights freezes gaze to the horizon. *Journal of Vestibular Research*, *24*(5-6), 433–441.

Legters, K. (2002, 03). Fear of Falling. *Physical Therapy*, *82*(3), 264-272.

Maki, B. E., Holliday, P. J., & Topper, A. K. (1991). Fear of falling and postural performance in the elderly. *Journal of gerontology*, *46*(4), M123–M131.

Maki, B. E., & McIlroy, W. (1996, Nov). Postural control in the older adult. *Clin Geriatr Med*, *12(4)*, 635-58.

Mergner, T., & Rosemeier, T. (1998, Nov). Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions–a conceptual model. *Brain Res Brain Res Rev*, *28(1-2)*, 118-35. doi: 10.1016/s0165-0173(98)00032-0

Misslin, R. (2003). The defense system of fear: behavior and neurocircuitry. *Neurophysiologie Clinique/Clinical Neurophysiology*, *33*(2), 55-66.

Nagai, K., Yamada, M., Uemura, K., Tanaka, B., Mori, S., Yamada, Y., … Tsuboyama, T. (2012). Effects of fear of falling on muscular coactivation during walking. *Aging clinical and experimental research*, *24*, 157–161.

Okada, S., Hirakawa, K., Takada, Y., & Kinoshita, H. (2001). Relationship between fear of falling and balancing ability during abrupt deceleration in aged women having similar habitual physical activities. *European journal of applied physiology*, *85*, 501–506.

Osler, C. J., Tersteeg, M. C. A., Reynolds, R. F., & Loram, I. D. (2013). Postural threat differentially affects the feedforward and feedback components of the vestibular-evoked balance response. *European Journal of Neuroscience*, *38*(8), 3239-3247.

Park, C., Atique, M. M. U., Mishra, R., & Najafi, B. (2022). Association between fall history and gait, balance, physical activity, depression, fear of falling, and motor capacity: A 6-month follow-up study. *International Journal of Environmental Research and Public Health*, *19*(17).

Ponzano, M., Gibbs, J. C., Adachi, J. D., Ashe, M. C., Cheung, A. M., Hill, K. D., … Giangregorio, L. M. (2020). Exploring fear of falling and exercise self-efficacy in older women with vertebral fractures. *Journal of aging and physical activity*, 1-6.

Rachman, S. (2004). Fear and courage: A psychological perspective. *Social Research*, *71(1)*, 149-176.

Reelick, M. F., van Iersel, M. B., Kessels, R. P., & Rikkert, M. G. O. (2009). The influence of fear of falling on gait and balance in older people. *Age and ageing*, *38*(4), 435–440.

Sawa, R., Doi, T., Misu, S., Tsutsumimoto, K., Nakakubo, S., Asai, T., … Ono, R. (2014). The association between fear of falling and gait variability in both leg and trunk movements. *Gait & posture*, *40 1*, 123-7.

Staab, J. P. (2014, Feb). The influence of anxiety on ocular motor control and gaze. *Curr Opin Neurol*, *27*(1), 118–124.

Stamenkovic, A., van der Veen, S. M., & Thomas, J. S.

(2020). Fear priming: a method for examining postural strategies associated with fear of falling. *Frontiers in aging neuroscience*, *12*, 241.

Teachman, B. A., Stefanucci, J. K., Clerkin, E. M., Cody, M. W., & Proffitt, D. R. (2008). A new mode of fear expression: perceptual bias in height fear. *Emotion*, *8*(2), 296.

Tinetti, M. E., Richman, D., & Powell, L. (1990, 11). Falls Efficacy as a Measure of Fear of Falling. *Journal of Gerontology*, *45*(6), P239-P243.

Todorov, E., & Jordan, M. (2002, Nov). Optimal feedback control as theory of motor coordination. *Nature Neuroscience*, *5*, 1226-35. doi: https://doi.org/10.1038/nn963

Vellas, B., Wayne, S., Romero, L., Baumgartner, R., & Garry, P. (1997, 05). Fear of fall and restriction of mobility in elderly fallers. *Age and ageing*, *26*, 189-93. doi: 10.1093/ageing/26.3.189

Wiederhold, B. K., & Bouchard, S. (2014). Fear of heights (acrophobia): Efficacy and lessons learned from psychophysiological data. *Advances in Virtual Reality and Anxiety Disorders*, 119–144.

Winter, D. (1995, Dec). Human balance and posture control during standing and walking. *Gait & Posture*, *3*, 193-214. doi: https://doi.org/10.1016/0966-6362(96)82849-9

Wolpert, D., & Miall, R. (1996, Nov). Forward models for physiological motor control. *Neural Netw.*, *9(8)*, 1265-79. doi: 10.1016/s0893-6080(96)00035-4

Wuehr, M., Breitkopf, K., Decker, J., Ibarra, G., Huppert, D., & Brandt, T. (2019). Fear of heights in virtual reality saturates 20 to 40 m above ground. *Journal of neurology*, *266*(Suppl 1), 80–87.

Wuehr, M., Kugler, G., Schniepp, R., Eckl, M., Pradhan, C., Jahn, K., … Brandt, T. (2014). Balance control and anti-gravity muscle activity during the experience of fear at heights. *Physiological Reports*, *2*(2), e00232.

Young, W., & Williams, A. (2015, Jan). How fear of falling can increase fall risk in older adults: applying psychological theory to practical observations. *Gait & posture*, *41(1)*, 7-12. doi: https://doi.org/10.1016/j.gaitpost.2014.09.006

Zaback, M., Adkin, A. L., & Carpenter, M. G. (2019, August). Adaptation of emotional state and standing balance parameters following repeated exposure to height-induced postural threat. *Scientific reports*, *9*(1), 12449.

Zaback, M., Luu, M. J., Adkin, A. L., & Carpenter, M. G. (2021). Selective preservation of changes to standing balance control despite psychological and autonomic habituation to a postural threat. *Scientific Reports*, *11*(1), 384.