



HOKKAIDO UNIVERSITY

Title	Research on knee joint function in standing posture control and its application in rehabilitation exercise therapy
Author(s)	江, 林京
Degree Grantor	北海道大学
Degree Name	博士(保健科学)
Dissertation Number	甲第15822号
Issue Date	2024-03-25
DOI	https://doi.org/10.14943/doctoral.k15822
Doc URL	https://hdl.handle.net/2115/93737
Type	doctoral thesis
File Information	Linjing_Jiang.pdf



学 位 論 文

Research on knee joint function in standing posture control and its
application in rehabilitation exercise therapy

(立位姿勢制御の膝関節機能と運動療法への応用についての研究)

Linjing Jiang

北海道大学大学院保健科学院

保健科学専攻保健科学コース

2023 年度

Contents

Abstract	vi
Background:	vi
Materials and Methods	vi
Results	viii
List of Abbreviations	xi
Chapter 1	- 1 -
General Introduction.....	- 1 -
1.1 Falls and Health Economic Issues	- 2 -
1.2 Rehabilitation/Physical Therapy for Balance and Fall Prevention	- 2 -
1.3 Postural Control.....	- 3 -
1.4 Postural Strategy.....	- 4 -
1.5 Knee Joint Function and Suspensory Strategy	- 6 -
1.6 Kinematic and kinetic Analysis for Sensorimotor System in Postural Control through Advanced Techniques	- 7 -
1.7 Research questions and Purpose	- 11 -
1.7.1 Dose the knee flexion changes the sensory integration during static standing?	- 12 -
1.7.2 Dose the knee flexion contributes to the postural stability and fall prevention during the external perturbation?	- 13 -

1.7.3 Can the contribution of the knee be found by visualizing the minimal joint motion?	- 14 -
Chapter 2	- 15 -
First Study	- 15 -
Effect of Postural Control Due to Suspensory Strategy during Static Standing Balance.....	- 15 -
2.1 Introduction	- 16 -
2.2 Methods	- 17 -
2.2.1 Participants and Equipment	- 17 -
2.2.2 Procedures	- 18 -
2.2.3 Data Collection and processing	- 19 -
2.2.4 Statistical Analyses	- 22 -
2.3 Results.....	- 23 -
2.4 Discussion	- 26 -
2.4.1 Postural sway amplitude	- 26 -
2.4.2 Sensory integration	- 28 -
2.4.3 Regularity of Postural Sway	- 29 -
2.5 Conclusion	- 30 -
Chapter 3	- 31 -
Second Study	- 31 -

Effect of Postural Control Due to Suspensory Strategy during Dynamical Balance .	- 31 -
3.1 Introduction	- 32 -
3.2 Methods	- 33 -
3.2.1 Participants	- 33 -
3.2.2 Equipment	- 34 -
3.2.3 Protocols	- 34 -
3.2.4 Data processing.....	- 36 -
3.2.5 Statistical Analysis	- 37 -
3.3 Results.....	- 39 -
3.4 Discussion	- 42 -
Chapter 4.....	- 46 -
Third Study	- 46 -
Visualizing the Suspensory Strategy and Elucidating its Complexity through Principal Component Analysis	- 46 -
4.1 Introduction	- 47 -
4.2 Methods	- 48 -
4.2.1 Participants	- 48 -
4.2.2 Equipment and Procedures.....	- 49 -
4.2.3 Data processing.....	- 49 -

4.2.4 Interpreting Video Data.....	- 50 -
4.3 Statistics	- 52 -
4.4 Results.....	- 52 -
4.5 Discussion	- 55 -
4.6 conclusion	- 58 -
Chapter 5.....	- 60 -
Summaries.....	- 60 -
5.1 Aim and Goals.....	- 61 -
5.2 Summaries	- 61 -
5.2.1 Suspensory Strategy and Static Balance Control	- 61 -
5.2.2 Suspensory Strategy and Dynamical Balance Control	- 61 -
5.2.3 Visualizing Suspensory Strategy	- 62 -
Chapter 6.....	- 63 -
Limitation.....	- 63 -
Chapter 7.....	- 65 -
Future prospects	- 65 -
Chapter 8.....	- 68 -
General Conclusion	- 68 -
References.....	- 70 -
Author's publications and conference presentations	- 90 -

Select List of Relevant Works	- 90 -
Lists of other works	- 91 -
Acknowledgements	- 94 -

Abstract

Background:

Falls among the elderly is a common health problem globally, the cost of injuries and care associated with falls have become a significant financial burden, particularly in southeast Asian countries, such as Japan and China. Also, the secondary aftereffects induced by falls decrease the activity of daily living and the quality of life of individuals and moreover impose a substantial care and mental burden on their families. The postural control has been studied to understand the standing equilibrium more than half century, and findings regarding the postural control have supplied many valuable information for the rehabilitation and the physical therapy to avoid falls for older adults and patients with motor disorders. The postural control during the standing posture is carried out through lower limb joints (i.e., hip, knee, and ankle). Although the hip and ankle strategy as the postural control in the anterior-posterior (AP) direction is well-known, postural controls in other directions (e.g., medial-lateral (ML) or vertical) are not focused on a little. Additionally, the role of knee for postural control remains unclear. This thesis focuses on knee joint function in standing posture control, investigates the impact of knee flexion on static and dynamic balance, and exploring the contribution of the knee on the postural control during the standing posture and avoiding falls.

Materials and Methods

Experimental Approach to the Problem

This study performed the cross-sectional randomized experiments including two conditions. Study 1 examined the changes in sensory integration on postural sway during static standing balance by knee flexion. Study 2 examined whether knee flexion, which is a suspensory strategy in postural control, contributes to postural stabilization for lateral perturbation. Finally, the contribution of the knee to postural control during the standing posture was assessed quantitatively using Principal Component Analysis (PCA)

Study 1: Nineteen healthy young adults (11 males and 8 females) participated in this experiment. Participants were instructed to keep three standing postures with knee flexion 0° , 15° , and 65° , respectively. Full-body marker set data for these postures were collected using a three-dimensional motion capture system and Visual 3D was used to calculate COM movements as the postural sway. Time-frequency analysis was used to assess the energy content across frequency bands at offline, and sample entropy was used to evaluate the regularity of the COM displacement patterns. Time-frequency analysis and sample entropy were utilized to clarify the relationship between the sensory integration and the postural sway.

Study 2: In this experiment, lateral perturbation tasks with three different velocities were added to Study 1. Eighteen healthy young adults (10 males and 8 females) participated in posture settings and data collection methods identical to those used in Study 1. Three lateral perturbation speeds (7 cm/s, 15 cm/s, and 20 cm/s) were introduced and participants were instructed maintain their standing or knee-flexed posture before and

after perturbations. The displacement and time parameters of the COM under these conditions were measured and used to analyze post-perturbation adjustments included reaction time, peak displacement/time, reversal time, and minimum margin of stability (minimum-MOS) to evaluate postural stability and control.

Study 3: The posture settings and data collection methods were consistent with those of Study 1. PCA was applied to analyze the full-body marker data and extract five principal movements. Qualitative descriptions were provided for these principal movements, and the relative variance and cumulative variance were calculated for each subject to assess the complexity of the structure (i.e., strategy) of the postural control.

Results

Study 1: The COM height during knee flexion lowered significantly compared with that without knee flexion. The highest energy content was occurred at knee flexion 65° in the full frequency band, in contrast to the lowest at 0° in both the antero-posterior (AP) and medio-lateral (ML) directions. The ultra-low-frequency band and very-low-frequency band prominence was greater at knee flexion 65° than at 0° or 15° in the ML direction. This suggests that knee flexion changes the balance-related sensory integration and sensory weights. COM amplitudes were notably higher at knee flexion 65° than at 0° and 15° in the AP and ML directions, respectively. The sample entropy values were lower

at knee flexion 65° and 15° than at 0° in the ML direction and reached the lowest value at knee flexion 65° in the vertical direction.

Study 2: COM reaction times for low and mid perturbation velocities were delayed at knee flexion 65° compared to knee flexion 0° and 15°. COM reversal times were significantly shorter at knee flexion 65° than at 0° and 15° across all perturbation velocities. Knee flexion 65° resulted in better recovery from perturbations; 65° of knee flexion showed a greater risk of falls from the minimal MOS data, and the minimum MOS at a high velocity of perturbation was significantly smaller at knee flexion 65° than at 0° and 15°.

Study 3: Ankle and hip joint strategies during knee flexion 0° were the first and second principal movements, respectively. The suspensory (i.e., knee) strategy was observed as the vertical principal movement during knee flexion 15° and 65°. Regarding movement complexity, significant differences in between knee flexion 15° and 65° were observed only for the fourth major movement component.

Conclusion

Suspensory strategy with knee flexion affects balance control in static and dynamic balance, with slight flexion improving stability, whereas excessive flexion leads to instability. Our findings suggest that the suspensory strategy performed by knee flexion has the special and unique role in the postural control and it is possible to contribute for

avoiding serious injuries induced by falls and for decreasing the risk of falls in older adults
and patients with motor disorders.

List of Abbreviations

Anterior posterior (AP)

Base of support (BOS)

Center of mass (COM)

Center of pressure (COP)

Cumulative relative variance (rCUM)

Margin of stability (MOS)

Medial lateral (ML)

Principal component (PC)

Principal component analysis (PCA)

Principal movement (PM)

Relative variance (rVAR)

Sample entropy (SampEn)

Chapter 1

General Introduction

1.1 Falls and Health Economic Issues

Approximately 30% of community-dwelling elderly individuals and those residing in long-term care facilities experience at least one fall per year (Robinovitch et al., 2013). It is of utmost importance to address the issue of falls among the elderly, as it not only causes physical and psychological distress, but also imposes a significant economic burden on healthcare systems (Montero-Odasso et al., 2021, Hu et al., 2021, Hayashi, 2007). In fact, studies have estimated that the annual cost of falls in China is approximately 700 million dollars (Hu et al., 2021) and in Japan, it about 2.5 billion dollars (Hayashi, 2007). Therefore, research focusing on fall prevention is critical for both individuals and the society as a whole.

1.2 Rehabilitation/Physical Therapy for Balance and Fall Prevention

Fall incidents among the elderly result from multiple risk factors (Tinetti et al., 1993; DeLisa et al., 2005; Gillespie et al., 2012; Robinovitch et al., 2013). Addressing the assessment and prevention of falls in this demographic needs a comprehensive multidisciplinary approach. The integration of intrinsic factors, such as diseases, medications, age-related vision impairments, and neuromuscular coordination issues, along with consideration of extrinsic factors such as environmental factors, is crucial (Gillespie et al., 2012). A holistic fall prevention program should systematically address these diverse elements to effectively decrease the risk of falls in the elderly. Rehabilitation

science and physical therapy play a pivotal role in this integrated approach, focusing on the treatment of exogenous factors, as well as the enhancement of neuromuscular strength and coordination (DeLisa et al., 2005; Gillespie et al., 2012). Comprehensive balance training encompassing strategies related to postural control is deemed indispensable for frail older adults and individuals experiencing disease-induced postural balance instability, as highlighted in clinical instructions and guidelines (DeLisa et al., 2005; Tinetti, 2003). To find the possibility to adopt the knee motion as the new specific strategy of fall prevention, this study will delve into a detailed exploration of the relationship between the knee joint and propose the postural control along with potential treatment modalities.

1.3 Postural Control

Most fall incidents occur during activities that involve weight transfer, path obstructions, collisions, and slippery surfaces (Robinovitch et al., 2013). To avoid falls in various situations, understanding how the postural control system stabilizes static or dynamic upright postures remains an important purpose in the field of rehabilitation, sports, and biomechanics. Postural control is a complex process and is roughly divided into two primary components: postural orientation and equilibrium (Horak & Macpherson, 1996; Alghwiri & Whitney, 2012; Horak, 2006). Postural orientation involves sensing the direction and/or position of the trunk and head in relation to the gravity, the base of

support (BOS), visual surroundings, and internal references. Also, balance-related sensory information from not only the visual system but also the somatosensory and vestibular system is integrated, and the relative weight placed on each input depends on the motor task and the environment (Horak, 2006). Postural equilibrium involves neuromuscular control to stabilize the center of mass (COM) during both internal and external perturbations. The maintenance of postural equilibrium is recognized by the coordination of movement strategies to stabilize COM in response to both self-initiated and externally induced disturbances. In previous research, postural equilibrium was usually parsed through the lens of neuromuscular control, joint strategies, central control strategies, etc. (Horak, 2006; Nashner & McCollum, 1985; Wachholz et al., 2019; Todorov, 2004; Todorov & Jordan, 2002).

1.4 Postural Strategy

Previous literatures suggest that postural control strategies utilized to maintain standing balance can be broadly classified into fixed and changed support surface balance strategies (Nashner & McCollum, 1985; Winter, 1995; Pollock et al., 2000). Within the context of fixed support surface studies, ankle and hip strategies are recognized as the primary mechanisms for maintaining upright balance (Nashner & McCollum, 1985; Winter, 1995). The ankle strategy is responsible for controlling the anterior-posterior (AP) direction balance and responding to minor perturbations,

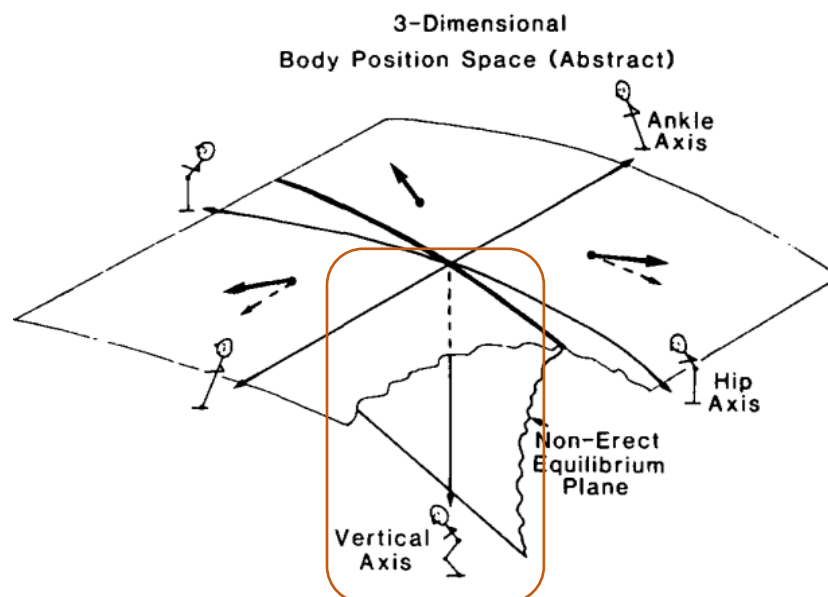


Figure 1. In 3-dimensional space, ankle and hip dorsiflexion and extension primarily induce movement in the horizontal direction of posture, while knee dorsiflexion and extension induce movement in the vertical axis. Figure taken from a study by Nashner and McCollum (1985).

whereas the hip strategy manages the AP direction and medial-lateral (ML) direction balance and plays a crucial role in handling disturbances, particularly on smaller support surfaces (Winter, 1995; Winter et al., 1996). Therefore, most studies have explored ankle and hip strategies in the horizontal plane in the AP and ML directions of the COM or center of pressure (COP). However, the advancement of biomechanics and motion-capture technology has revealed that joint strategies related to postural control often overlap, and the distinctions between these strategies are not always clear (Runge et al., 1999). Although Nashner and McCollum (1985) considered the suspensory strategy with

the knee to control the COM in the vertical direction besides the hip and ankle strategy (Figure 1), the feature of the knee joint in the vertical balance control while standing may be overlooked little for a long time because the amplitude of the knee motion was very small (Rung et al., 1999; Kasahara et al., 2015; Cheng, 2016).

1.5 Knee Joint Function and Suspensory Strategy

Although the original concept of the three-dimensional postural control was established in the 20th century and the vertical postural control was referred to in literature as the "suspensory strategy", it is not clear how the suspensory strategy with the knee flexion can actually contribute to balance control (Nashner & McCollum, 1985; Alghwiri & Whitney, 2012; Kasahara et al., 2015). Also, since there is a paucity of research on the vertical postural strategy until now, it is still controversial whether there are beneficial effects on balance through flexion of the knee. For example, Sugama et al. (2020) found that flexion of the knee lowered the functional stability limits while altering the moments in the lower limb, and however, others reported that lowered COM position and consequently, improved more stable balance performance (Rosker et al., 2011; Kasahara et al., 2015). Likewise, other studies simulating human movement have also found that slight flexion of the knee may provide benefits for standing balance (Iqbal & Pai, 2000; Cheng & Yeh, 2015). Furthermore, as the dynamic balance postural control, the knee

flexion is considered to be able to absorb the shock during jump landing (Kim et al., 2017; Coventry et al., 2006) and during the external perturbation (Di Giulio et al., 2013).

In general, it is the common idea that the flexion posture is 'poor' and this 'poor posture' in clinical practice is considered to be a posture that needs to be improved (Benedetti et al., 2008). However, as mentioned above, the knee flexion posture, that is the suspensory postural strategy with the knee has a sense of possibility to stabilize the posture from the view of the postural control. Previous study in our lab has also found that older people use knee flexion to add balance to the posterior (Kasahara et al., 2015). Although there are different perceptions of bent knees between researches, the suspensory postural strategy with the knee would be used as an effective compensatory way to achieve a more stable posture (Kasahara et al., 2015). Thus, to emphasize this requires further parsing of the balance-related data.

1.6 Kinematic and kinetic Analysis for Sensorimotor System in Postural Control through Advanced Techniques

Postural control, encompassing both postural orientation and equilibrium, has traditionally been examined using kinematic and kinetics data, for example, joint motions, joint moments, the center of mass (COM), and the center of pressure (COP). Also, the COM or COP movement represents the combined effects of numerous neuromusculoskeletal components operating at various joint levels, reflecting the output of a highly integrated system that effectively assesses postural stability and provides

valuable insights into postural balance (Winter, 1995; Horak, 2006). However, these data themselves lack the ability to offer explicit physiological interpretations (Kędziorek & Michalina, 2020).

Postural control is performed at the foundation of the sensorimotor system and sensory information is always required for postural orientation and equilibrium. A growing number of experimental approaches in the field of balance control use time-frequency analysis to analyze COM or COP data and correlate balance-related sensory systems to determine changes in parameters related to balance orientation (Lin et al., 2019; Liang et al., 2014). Time-frequency analysis as methods have been increasingly used to analyze balancing data to the sensory integration associated with postural orientation in recent years (Lin et al., 2019; Borg & Laxåback, 2010; Assländer & Peterka, 2014; Kędziorek & Błażkiewicz, 2020). Time-frequency analysis of COP and COM is recommended for studying human posture control, as it is believed to offer a better understanding of the underlying mechanisms, such as sensory integration or sensory weighting in static balance, than traditional measures, such as amplitude, average velocity, or area (Lin et al., 2019; Assländer & Peterka, 2014; Chagdes et al., 2009). In previous studies, balance-related sensory systems corresponded to different frequency ranges of COM movement, and although some overlapping regions have been found among frequency in terms of basic research, they are usually divided into 3-4 bands in order to better explore sensory weights. In the present study, we adopted Lin et al. (2019) segmentation by dividing the

frequency bands into four bands: (1) ultra-low frequency band (below 0.1 Hz), (2) very low frequency band (0.10-0.39 Hz), (3) low-frequency band (0.39-1.56 Hz), and (4) mid-frequency band (1.56-6.25 Hz), which correspond to the visual, vestibular, cerebellar, and proprioceptive systems, respectively (Lin et al., 2019; Assländer & Peterka, 2014; Chagdes et al., 2009; Lam et al., 2016; Friedrich et al., 2008; Kapteyn & de Wit, 1972; Mauritz & Dietz, 1980). This process is often considered a process of sensory orientation, whereby the processing of sensory information allows the center to continuously acquire and update the postural state of the body (Figure 2).

Balance-related sensory integration also can change postural balance strategy, and there are many definitions of strategies for postural balance in previous research (Horak,

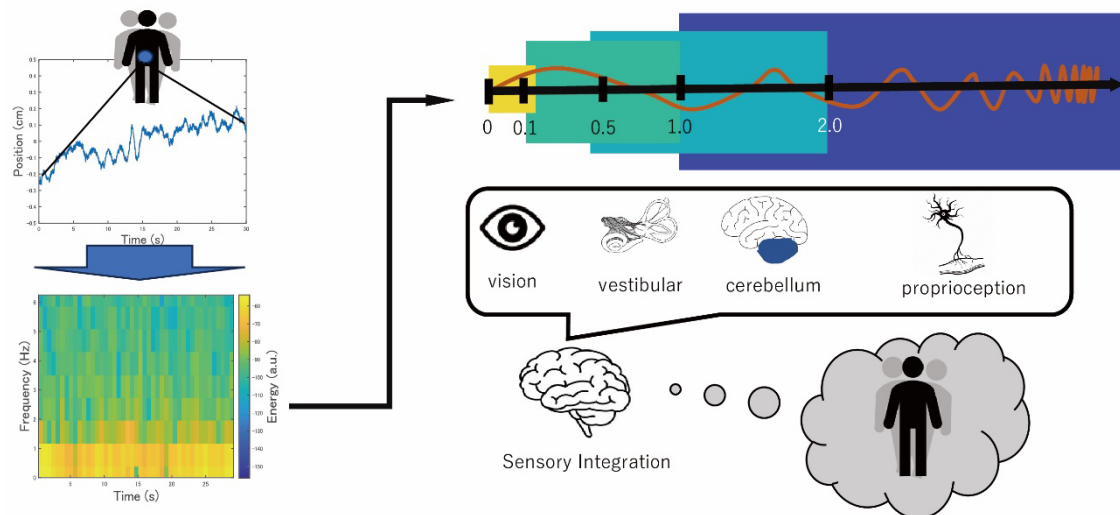


Figure 2. The feedback system for posture orientation to perceive movements involves sensory processing, in which the cerebellar system regulates the visual, vestibular, and proprioceptive inputs. The inputs of these sensory systems can be detected during body movements, as shown in the figure, where different frequency bands extracted from the trajectory of the COM movement correspond to different sensory feedback systems.

2006; Liang et al., 2014). In addition to the joint strategies described above, some control strategies that have been mentioned and are widely accepted in research, including the Optimal Feedback Control Theory and the Minimal Intervention Principle, have been suggested to explain different motor strategies during balance tasks or posture control (Wachholz et al., 2020; Todorov, 2004; Todorov & Jordan, 2002). The principle of minimal intervention suggests that a better balance strategy tends to imply more automated balance control. In other words, muscle activity intervenes only when there is a threat to balance in the presence of posture, and it is permissible to have lower regularity in postural control when the CNS determines that the posture is still in the equilibrium range (Todorov & Jordan, 2002). An increasing number of recent studies have used sample entropy to analyze the regularity of balance data to determine whether central control is consistent with a minimizing control strategy to evaluate posture equilibrium (Richman & Moorman, 2000; Borg & Laxåback, 2010; Assländer & Peterka, 2014).

On the postural control during the standing posture, it was first thought that lower-limb joint movements may contain both single and mixed joint strategies (Nashner & McCollum, 1985; Kasahara et al., 2015). Although early studies have questioned whether joint strategies act independently (Rung et al., 1999), in recent years, with the application of Principal Component Analysis (PCA) in the field of kinematics, this question has gradually begun to become clearer regarding whether single joint strategies or multi-joint strategies are present in a given balance task (Haid & Federolf, 2018; Haid et al., 2019).

For example, although we sometimes observe that both the ankle and hip joints produce movements during standing balance control, it may be difficult to distinguish whether these two joint strategies contribute independently or synergistically to whole-body kinematics. This problem is well solved by PCA, which in the field of kinematic analysis extracts principal movement (unrelated to other movements), a method that can effectively distinguish the presence of a single or mixed joint strategy and the cumulative contribution ratio.

In recent years, there has been a growing trend towards the adoption of nonlinear analysis, time-frequency analysis, and PCA to comprehensively investigate postural complexity, orientation, and principal movement extraction (Kędziorek & Michalina, 2020; Lin et al., 2019; Richman & Moorman, 2000, Haid et al., 2019). These methods offer a holistic and intuitive approach to the analysis of postural control, allowing for a deeper understanding of the balance control of underlying physiological mechanisms. This thesis used these methodologies and analyses to assess the postural control based on the sensorimotor system.

1.7 Research questions and Purpose

The overall goal of this thesis is to contribute to the understanding of sensorimotor system changes brought about by knee flexion in the upright position, as well as to

visualize joint strategies. Three studies have been conducted on this thesis. The first study aimed to understand the effects of knee flexion on static balance. The second study investigated the role of knee flexion during perturbations. The third study used the PManalyzer software developed by Haid et al. (2018) to extract the principal movements in different standing postures and reproduce them by means of video to better present the share of different joint strategies in the balance. The rest of this section elaborates on the importance and specifics of the research questions.

1.7.1 Dose the knee flexion changes the sensory integration during static standing?

As described in Chapter 1.3, although the suspensory postural strategy with the knee flexion was proposed in the 20th century (Nashner & McCollum, 1985), it remains inconclusive whether the suspensory postural strategy can actually contribute for the overall process of balance orientation and equilibrium during the standing posture. Most of the aforementioned studies have focused on linear changes in balance metrics or instantaneous data in studies related to knee flexion or suspensory strategy, but have rarely captured and included data on the temporal component in their analyses (Kędziorek & Michalina, 2020; Yentes & Raffalt, 2021). Therefore, the main purpose of the first study was to explore whether knee flexion affects sensory integration through time-frequency

analysis and whether the central control strategy changes in the horizontal overhead and vertical directions through sample entropy analysis of COM.

1.7.2 Dose the knee flexion contributes to the postural stability and fall prevention during the external perturbation?

Lateral falls in older adults are more likely to result in hip fractures, which are associated with a high risk of death in older adults (Maki & McIlroy, 2006) and thus, lateral perturbations are often recognized as tests that can effectively predict fall risk (Hilliard et al., 2008; Siragy et al., 2023). Several studies with lateral rotational perturbations found that both active and passive knee flexion and extension are beneficial for balance control (Oude Nijhuis et al., 2007; Allum et al., 2003; Bakker et al., 2006). For example, focusing mainly on lateral rotation perturbation, found that patients with spinocerebellar ataxia lacked knee flexion and extension following perturbation, suggesting that this was a major factor in instability (Bakker et al., 2006), and that actively incorporating the suspensory postural strategy may reduce the risk of injury following a fall from the high COM position by lowering the COM position (Oude Nijhuis et al., 2007). However, Oude Nijhuis et al. (2007) in the same study found that if subjects are not well-adapted to the knee flexion voluntary, it is possible that active knee flexion during perturbations may result in excessive backward movement of the COM, which could lead to negative effects on balance. Troy et al. (2008) found that a participant in his experiment recovered balance after lowering their COM (21.4 cm) following a lateral

perturbation. These studies (Oude Nijhuis et al. 2007; Troy et al. 2008) suggest that there is an adequate angle of the knee flexion for the lateral perturbation. The second study aimed to characterize the effect of the adequate knee flexion on the balance sequence after lateral perturbation.

1.7.3 Can the contribution of the knee be found by visualizing the minimal joint motion?

Since the actual knee motion is very small in the postural control during the static standing posture, the suspensory postural strategy has been ignored for a long time (Kasahara et al., 2015). Therefore, it was difficult to assess the role of the knee in the postural control. Study 3 attempted to show the positive effect of the knee function in the postural control during the static standing posture. Specifically, to confirm whether different lower limb joint strategies affect postural control in a specific posture or a specific balance task, Study 3 performed the principal component analysis with the PManalyzer from whole-body kinematic video data (Haid et al., 2018).

Chapter 2

First Study

Effect of Postural Control Due to Suspensory Strategy during Static Standing Balance

2.1 Introduction

The human body employs various postural strategies and mechanisms that are continually adjusted based on sensory information from multiple sources including the visual, vestibular, and somatosensory systems (Horak, 2006; Nashner & McCollum, 1985). This sensory information, central processing, and muscle activity finally produce the joint activity used to maintain balance (Horak, 2006; Fino et al., 2017). Although the postural control consists of three types of postural strategies, the mixed ankle and hip strategy is often used in actual. Nevertheless, most studies have examined the relationship between the sensory information and the balance ability only in either ankle or hip postural strategy (Horak, 1987; Horak, 2006; Runge et al., 1999). Moreover, the balance ability has been assessed with the index on the transversal plane, such as the amplitude, the trajectory length, and the rectangular area of the COP until now and the features of the multidirectional body sway including the vertical direction have not been noted as the analysis object.

Recently, the regularity of postural sway has been used to explain changes in the central control strategy (Kędziorek & Błażkiewicz, 2020) and the change for the sensory modality explaining postural orientation (Lin et al., 2019; Assländer & Peterka, 2014; 2014; Chagdes et al., 2009; Lam et al., 2016; Friedrich et al., 2008; Kapteyn & de Wit, 1972; Mauritz & Dietz, 1980).

In Study 1, it is aimed to clarify the change in postural orientation and equilibrium

using the time-frequency analysis and nonlinear analysis of the COM sway during the suspensory postural strategy. This study hypothesized that a static standing posture with knee flexion alters the sensory integration and balance on central control patterns.

2.2 Methods

2.2.1 Participants and Equipment

Nineteen healthy young adults (11 males and 8 females; mean age $\pm$ SD, 24.3 $\pm$ 2.2 years; age range, 21–30 years; weight, 62.7 $\pm$ 13.8 kg; and height, 169.5 $\pm$ 5.9 cm) were enrolled in this study. The participants with any current or past orthopedic or neurological illnesses were excluded from the study. Prior to inclusion, the participants were informed about the study and they signed a consent form for participation in this study. Consequently, all the participants were enrolled in this study. This study was approved by the review board of our institution (22–66) and conducted in accordance with the ethical guidelines set forth by the 1964 Declaration of Helsinki.

Three-dimensional motion capture kinematic data were acquired using seven high-speed cameras (Hawk Cameras; Motion Analysis Corp., Santa Rosa, CA, USA). The collected data were analyzed using a motion analysis system (Cortex version 5.0.1, Motion Analysis Corp.). Thirty-five retroreflective markers were placed at the specific anatomical points (Damiano et al., 2013; Ueno et al., 2020). Markers were placed on the front and back of the head, shoulders, elbows, and wrists. Markers were also placed on the seven cervical vertebrae, sternum, scapula, anterior and posterior iliac spines (ASIS

and PSIS, respectively), lateral thigh, medial and lateral femoral epicondyle, lateral shank, medial and lateral malleolus, second metatarsal head, fifth metatarsal head, and heel. The marker coordinate data were collected at a sampling rate of 200 Hz.

2.2.2 Procedures

To manipulate the suspensory strategy, participants were instructed to adopt three different postures with 0° (knee is locked by screw home mechanism) (Masouros et al., 2010; Kim et al., 2015), 15° (provide active stabilization and enable elastic absorption) (Di Giulio et al., 2013, Masouros et al., 2010), and 65° (with lower stiffness, which may lead to separation of the head from the whole-body movement) (Lam et al., 2016) of knee flexion (Figure 3). The feet were positioned at the same place with the interval as the hip width, and had the same orientation in all postures. No specific instructions were provided regarding the other joints. No specific instructions were provided regarding the other joints. To stabilize their gaze and avoid exceeding the bending posture, participants were asked to gaze at the fixation point with a 9-cm diameter circle at approximately 5 m in front of them across all tasks. The participants practiced the postures beforehand and received feedback from examiners to correct any errors during the trials. Knee joint angles and COM heights were verified to ensure compliance with the experimental design every trial. The experimental procedure involved asking the participants to stand in each of the three positions for at least 35 seconds, with the order of the positions randomized. The

participants were instructed to maintain each posture with different knee flexion angles for at least 35 seconds, and the order of the postures was randomized. After recording the data in one posture, the participants returned to a relaxed standing posture and rested for 10 seconds until the next posture. Ideally, there were no rest periods between each two postures, but if the participants experienced fatigue during the experiment, a 5-minute break was provided.

2.2.3 Data Collection and processing

Kinematic data, including knee joint angles and COM position, were analyzed using Visual3D software (version 6, C-Motion, Inc., Germantown, MD, USA) and processed with MATLAB (MATLAB 2022b, The MathWorks, Inc., Natick, MA, USA). A fourth-order, zero-lag Butterworth filter with a 10-Hz cutoff frequency was applied to the kinematic data to obtain a low-pass filtered signal (Kasahara et al., 2015). For the next data processing session, 30 seconds of kinematic data were extracted from the recorded data 35 seconds after visually confirming the knee angle and postural stability. In concrete terms, the knee angle was measured using a goniometer before recording the data, and then the knee angle was confirmed using Visual3D software offline data processing after recording. If the knee angle was incorrect, participants were asked to hold their posture again. The COM sway amplitudes in the AP, ML, and vertical directions were calculated at the selected analysis intervals and normalized according to the height of each

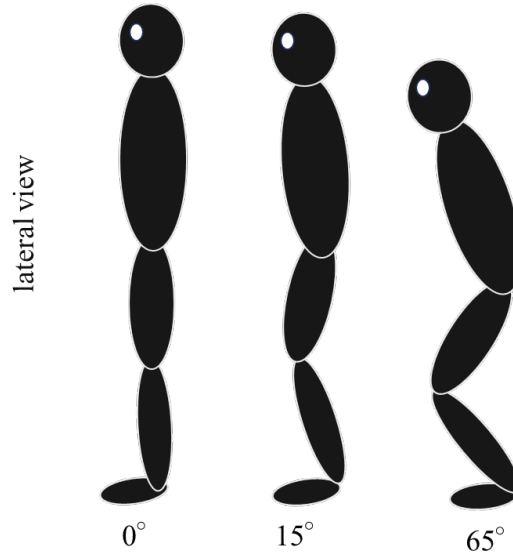


Figure 3. Representative pictures of standing at three knee flexion angles (0°, 15°, and 65°).

participant. The COM height was calculated as the average COM height at the selected analysis intervals and normalized to the height of each participant (Kasahara et al., 2015).

In accordance with prior studies (Lin et al., 2019, Assländer & Peterka, 2014), a time-frequency analysis was conducted on the AP and ML directions of the COM to explore the sensory energy input in the current study. Specifically, the COM signal was processed using Gabor transform, which is a time-frequency analysis technique used to extract the energy content during different frequency band of the signals. The Gabor transform is shown in Eq. (1).

$$G(t, f) = \int_{-\infty}^{+\infty} x(\tau) e^{-\sigma\pi(t-\tau)^2} e^{-j2\pi f\tau} d\tau \quad (1)$$

The Gaussian window with a width controlled by parameter σ in Equation (1) is

represented by output $G(t, f)$, which displays the central oscillator location at various frequencies. The integral of $G(t, f)$ along the frequency axis represents the accumulation of information from different frequency bands.

The total energy content was determined by adding the energy in the frequency range of 0–6.25 Hz (Lin et al., 2019). To assess alterations in the proportion of energy content from different sensory systems, the frequency range was divided into four bands: 1) ultra-low-frequency band (below 0.1 Hz; visual system); 2) very-low-frequency band (0.10–0.39 Hz; vestibular system); 3) low-frequency band (0.39–1.56 Hz; cerebellar system), and 4) moderate-frequency band (1.56–6.25 Hz; proprioception system), respectively (Lin et al., 2019; Assländer & Peterka, 2014; Chagdes et al., 2009; Lam et al., 2016; Friedrich et al., 2008; Kapteyn & de Wit, 1972; Mauritz & Dietz, 1980). The local energy content of each frequency band was calculated as a percentage of the total energy by referring to the sensory weights (Lin et al., 2019; Liang et al., 2014; Quek et al., 2014).

Sample entropy was previously used to analyze the regularity of postural sway data during static standing (Borg & Laxaback., 2010; Haid et al., 2018). Thus, it was calculated for the AP, ML, and vertical COM displacements. The computation method for sample entropy was implemented using an approach developed by Richman and Moorman, which was translated into MATLAB functions and utilized for further calculations (Haid et al., 2018; Buchecker et al., 2018; Ramdani et al., 2009). The sample entropy is shown in Equations (2, 3, and 4).

$$\text{Sample entropy } (m, r, N) = -\ln\left(\frac{A}{B}\right) \quad (2)$$

$$A = \left(\frac{(N-m-1)(N-m)}{2}\right)A^m(r) \quad (3)$$

$$B = \left(\frac{(N-m-1)(N-m)}{2}\right)B^m(r) \quad (4)$$

The length of the sequences to be compared is denoted by m , the tolerance value for accepting matches is denoted by r , the length of the data is denoted by N , the probability that sequences match for $m+1$ point is denoted by $A^m(r)$, and the probability that sequences match for m point is denoted by $B^m(r)$. However, there is no consensus on the parameter selection, but for balance control studies, the parameter settings are commonly set to $m = 2$ or 3 and r between 0.1 and 0.25 standard deviation (SD) (Richman & Moorman, 2000). For this study, the parameters were set as $m = 2$ and $r = 0.2$ multiplied by the SD (Haid et al., 2018; Buchecker et al., 2018; Ramdani et al., 2009). Generally, the sample entropy value approaches zero for a perfect regularity pattern. Conversely, if the signal has more irregularity, the sample entropy value tends to be higher (Buchecker et al. 2018, Ramdani et al., 2009).

2.2.4 Statistical Analyses

All statistical analyses were performed using SPSS Statistics (version 18.0; IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test was conducted to test normality. One-way repeated-measures analysis of variance (ANOVA) or Friedman’s test was used to examine the effects of posture (three different degrees of knee flexion) on the outcome measure.

Post-hoc analyses between the two postures with different knee flexions were conducted using the Bonferroni paired comparison method or pairwise comparisons. For one-way repeated-measures ANOVA, Cohen suggested that small, medium, and large effects would be reflected in the partial eta squared values (η^2) to 0.01, 0.06, and 0.14 (Cohen, 2013). According to Cohen's guidelines, Kendall's W value was used for Friedman's test, with values in the range of 0.1–0.3 indicating a small effect, values in the range of 0.3–0.5 indicating a moderate effect, and values ≥ 0.5 indicating a large effect (Cohen, 2013). The significance level was set at a P-value < 0.05 .

2.3 Results

In Figure 4, the COM height data for three knee flexion postures indicate a significant effect of knee flexion angle on COM height ($\chi^2 (2) = 38.00$, $P < 0.001$, Kendall's $W = 1.00$). Post-hoc analyses confirmed differences COM between the knee flexion (all $P < 0.001$).

Significant differences existed in COM sway in the AP ($\chi^2 (2) = 8.84$, $P < 0.05$, Kendall's $W = 0.23$), ML ($\chi^2 (2) = 17.16$, $P < 0.001$, Kendall's $W = 0.45$), and vertical directions ($\chi^2 (2) = 34.11$, $P < 0.001$, Kendall's $W = 0.90$). Post hoc analyses revealed specific pairwise differences (Figure 5).

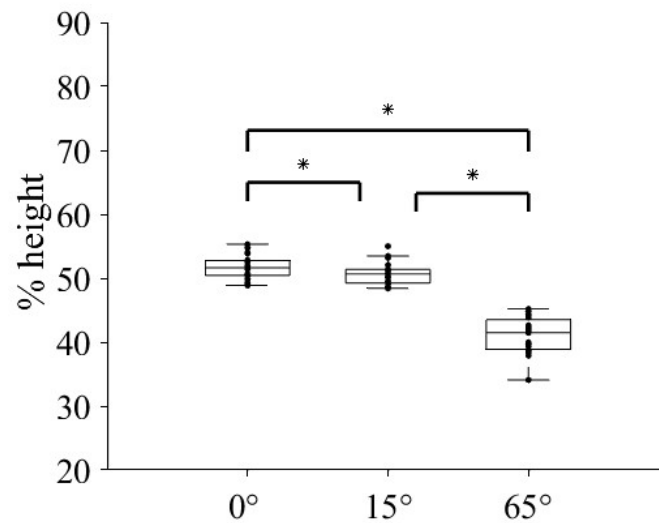


Figure 4. Comparison of the COM height (%) between 0°, 15°, and 65° knee flexion. * indicates $P < 0.05$. The box plot represents the median values and interquartile range of the entire sample for each measurement and displays the maximum and minimum values through the upper and lower whiskers.

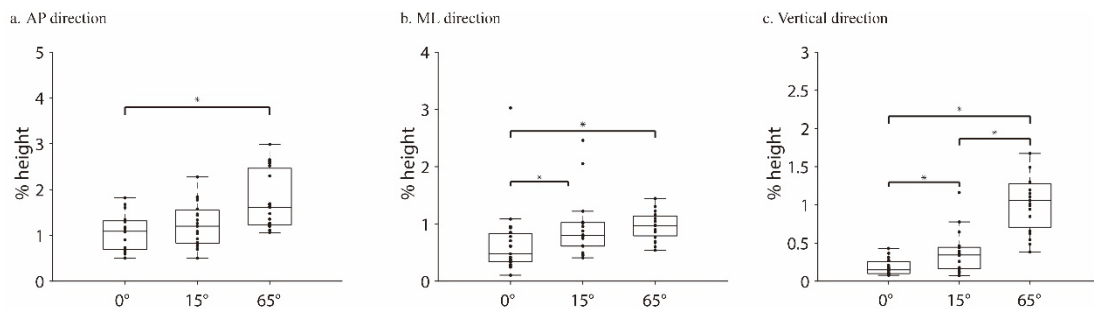


Figure 5. Comparison of COM sway (height %) between 0°, 15°, and 65° knee flexion in AP(a), ML(b), and vertical (c) directions. * indicates $P < 0.05$. The box plot represents the median values and interquartile range of the entire sample for each measurement and displays the maximum and minimum values through the upper and lower whiskers.

The total energy content of all frequency bands in the COM AP direction significantly differed among the knee flexion angles ($\chi^2(2) = 14.632$, $P < 0.001$, Kendall's $W = 0.39$).

Post hoc analyses showed a lower total energy content at 65° knee flexion than at 0° and

	COM direction	Knee flexion angle		
		0°	15°	65°
Total energy content (A.U.)	AP	3.50(2.74, 4.97)	4.63(3.45, 5.82)	5.78(5.16, 9.42)* #
	ML	1.72(1.34, 3.18)	2.75(2.17, 3.37)*	3.79(3.16, 4.14)* #
ultra-low-frequency band (%) (below 0.1 Hz)	AP	28.79 (25.67, 33.47)	26.36(23.89, 37.00)	31.52(25.17, 37.63)
	ML	27.79(23.09, 34.74)	29.88(26.68, 35.46)	25.70(20.46, 27.40)* #
very-low-frequency band (%) (0.10-0.39 Hz)	AP	29.47(23.56, 35.04)	30.31(24.13, 34.88)	27.83(23.91, 33.74)* #
	ML	25.01(22.52, 28.60)	29.76(22.00, 31.91)	36.56(32.74, 37.91)* #
low-frequency band (%) (0.39-1.56 Hz)	AP	22.23(20.26, 24.22)	22.21(18.91, 25.12)	22.21(17.99, 25.19)
	ML	26.57(23.05, 30.62)	23.68(20.45, 26.99)	25.19(24.61, 27.68)
moderate-frequency band (%) (1.56-6.25 Hz)	AP	17.88(15.20, 21.27)	18.77(13.86, 22.20)	18.07(12.93, 22.20)
	ML	17.26(15.54, 21.81)	14.48(10.54, 17.72)	15.14(12.09, 19.35)

Table 1. The median (Q1, Q3) deviation for Total energy content of the COM AP and ML directions, and the percentage of energy content in each frequency band in the COM AP and COM ML directions. AP, anterior-posterior direction; ML, medial-lateral direction; *P < 0.05, compared with 0° knee flexion; #P < 0.05, compared with 15° knee flexion.

15° (both P < 0.05; Table 1). No significant differences were observed in ultralow-, low-, and moderate-frequency bands (Table 1.). However, the very-low-frequency band showed a significant difference ($F(2, 36) = 5.71$, $P < 0.05$, $\eta^2 = 0.24$), with lower energy percentage at 65° than at 0° and 15° ($P < 0.05$; Table 1.).

Similar patterns were observed in the COM ML direction compared to the AP direction, with significant differences in the total energy content ($\chi^2(2) = 20.632$, $P < 0.001$,

Kendall's $W = 0.543$). Post-hoc analyses indicated a lower total energy content at 65° than at 0° and 15° (both $P < 0.05$; Table 1.). No significant differences were found between the low- and moderate-frequency bands (Table 1.). However, significant differences were observed in the ultra-low- and very-low-frequency bands (Table 1.).

Sample entropy analysis indicated no significant difference in the COM in the AP direction ($\chi^2 (2) = 4.11$, $P = 0.13$, Kendall's $W = 0.23$). However, significant differences were observed in the COM ML direction ($\chi^2 (2) = 15.47$, $P < 0.001$, Kendall's $W = 0.45$) and the vertical direction ($\chi^2 (2) = 21.72$, $P < 0.001$, Kendall's $W = 0.87$), with specific pairwise differences (Figure 6).

2.4 Discussion

2.4.1 Postural sway amplitude

In static standing, the amplitude of COM sway is typically inversely correlated with balance ability, where smaller amplitudes signify better balance (Horak, 2006; Adkin & Carpenter, 2018). However, certain factors such as heightened tension (Fischer et

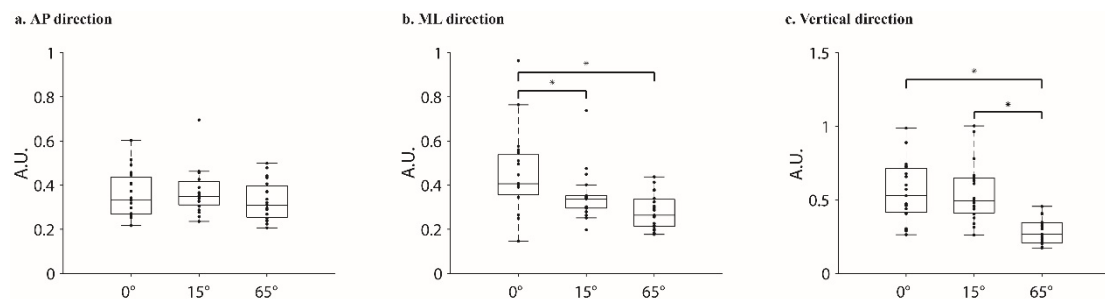


Figure 6. Comparison of SampEn between 0° , 15° , and 65° knee flexion in AP(a), ML(b), and vertical (c) directions. * indicates $P < 0.05$. The box plot represents the median values and interquartile range of the entire sample for each measurement and displays the maximum and minimum values through the upper and lower whiskers.

al., 2023), postural stiffness (Adkin & Carpenter, 2018), and reduced attention (Huxhold et al., 2006) have been shown to decrease postural sway length in AP or ML direction, complicating the interpretation of these changes in relation to balance improvement. This work observed a slight increase in COM sway amplitude in the AP and ML directions, with no apparent threat to balance. Notably, significant changes of COM amplitude were observed in the vertical direction during knee flexion, suggesting potential exploratory mechanisms.

Previous research (Huxhold et al., 2006; Riccio & Stoffregen, 1988; Adkin & Carpenter, 2018; Carpenter et al., 2010) propose that small increases in COM sway in the horizontal plane may indicate functional adaptations rather than clear improvements or deteriorations in balance. The observed changes in COM sway in the vertical direction during knee flexion may be linked to increased lower limb freedom, allowing for the utilization of suspensory strategies for balance control (Nashner & McCollum., 1985; Kasahara et al., 2015). However, the existence of a TRADE-OFF phenomenon in postural control suggests that enhanced stabilization and the benefits of larger postural sway may not coexist. Further investigations are necessary to elucidate the effects of suspensory strategies, particularly during perturbations, and to determine whether knee flexion can indeed lead to improved stabilization across various environments.

2.4.2 Sensory integration

This study also aimed to explore the effects of knee flexion on sensory integration with respect to postural orientation. The time-frequency analysis of the COM or COP is commonly used to explore sensory input and measure sensory reweighting (Lin et al., 2019; Chagdes et al., 2009; Peterka, 2018; Liang et al., 2014). Previous research has suggested that an increase in sensory energy within the 0–6.25 Hz frequency range correlates with an increase in balance-related sensory input (Lin et al., 2019, Assländer & Peterka, 2014). This study found that balance-related sensory integration changed during knee flexion in both the AP and ML directions. These findings may help explain why older people prefer the suspensory strategy of knee flexion with a lowered COM for balance control when performing internal perturbations (Kasahara et al., 2015), as balance-related sensory functions decline with age (Goble et al., 2009; Kal et al., 2022; Carpenter et al., 2010), and the changed sensory integration from knee flexion may compensate for this sensory deficit. In terms of the sensory weights in the AP direction, the present study only showed a decrease in the vestibular sensory-related weights when the knee flexion was 65°. Interestingly, in the ML direction, the present study showed that in the knee flexion, the visual-related weights decreased, but the vestibular-related sensory weights increased (Lin et al., 2019; Chagdes et al., 2009; Liang et al., 2014). This suggests that the suspensory strategy by knee flexion changes the balance-related sensory integration simultaneously with changes in the balance-related sensory weights, and that

this change is inconsistent in the AP and ML directions of balance. Therefore, a suspensory strategy of knee flexion may compensate for some deficits in the balance-related sensory acquisition to increase postural control and alter the balance-related sensory weights in the standing balance.

2.4.3 Regularity of Postural Sway

The relationship between sample entropy and postural sway is generally intuitive: a decrease in sample entropy corresponds to more regular and controlled postures, whereas increases in sample entropy indicate less regular and more automatic postures (Borg & Laxaback, 2010; Fischer et al., 2023). The results of this study show that a decrease in passive stability is accompanied by an increase in active stability during static standing with flexed knees, suggesting that there is more muscle activity and more attention to postural stability in a knee flexion posture (Masouros et al. 2010; Lam et al. 2016; Kędziorek & Blazkiewicz. 2021), and these results were only observed in the ML and vertical directions have been observed. While most studies on the relationship between sample entropy and postural control agree that lower sample entropy tends to reveal more rigid and inflexible postural control, and that too much attention is paid to balance control, which also tends to predict poor balance control (Donker et al., 2007; Borg & Laxaback, 2010). However, it has also been suggested that lower entropy may not only represent excessive postural rigidity, but also an appropriate level of regularity in postural control

(Montesinos et al., 2018; Borg & Laxaback, 2010). These studies have suggested that, although postural control needs to reflect a certain degree of physiological regularity, sometimes too much regularity may indicate that the postural control mechanism is too stochastic to control balance very well.

2.5 Conclusion

Combined with the discussion in the three sections above, the main finding of this study is that knee flexion posture has an effect on balance control, in which the whole amplitude of COM becomes larger, while the results of the time-frequency analysis related to sensory integration change, and the results of the sample entropy show an increase in regularity in the left-right versus vertical direction in the squatting posture. In conjunction with these results, this study suggests that changes in balance-related parameters in the knee flexion posture may explain the use of knee flexion to increase postural control, such as changed sensory integration, perception of balance, and voluntary control. Therefore, the suspension strategy with knee flexion is a compensatory posture that may be used by older adults and patients with diminished sensory and neuromuscular controls.

Chapter 3

Second Study

Effect of Postural Control Due to Suspensory Strategy during Dynamical Balance

3.1 Introduction

Falls are often induced by not only the internal but also the external perturbation. Therefore, the postural control must act adequately to stabilize the posture and to avoid falls for the external perturbation. With increasing the amplitude of the external perturbation, it is well known that the hip or step strategy is adopted from the ankle strategy to avoid falls (Horak, 2006; Runge et al., 1999). The suspensory strategy has the potential to decrease the risk of serious injury in falls (Nashner & McCollum, 1985; Alghwiri & Whitney, 2012; Kasahara et al., 2015). Lowering the COM height involves bringing the weight closer to the ground, which improves the balance stability (Alghwiri & Whitney, 2012; Hof et al., 2005). Additionally, Rosker et al. (2011) found that lowering the COM height by adding an additional load suspended from the waist at the mid-lower leg height during standing balance can decrease COM sway during static standing. Our previous study also found that older adults may use lightly flexed knee joints to lower COM height and prevent falls when controlling posterior direction balance (Kasahara et al., 2015). When the knee joint is flexed by 15° – 30° , it disrupts the stability of the joint surface, ligaments, menisci, and retinacula, requiring increased muscle activity in the lower limb (Kim et al., 2015; Masouros et al., 2010; Wretenberg et al., 2002). However, increased muscle contraction in the lower limbs is believed to enhance active stability, which can help with energy absorption or adjustment to disturbances (Masouros et al., 2010).

Ankle and hip strategies are considered to contribute the anteroposterior balance control more than the lateral balance control. Therefore, there is no effective strategy to absorb the lateral perturbation, the step strategy is selected easily. The step strategy requires the new base of support and however, it is difficult to perform the step strategy as possible as fast for older adults and patient with motor disorders.

The purpose of Study 2 was to show the positive effect of incorporating the knee flexion (i.e., the suspensory postural strategy) actively for the postural stability during sudden lateral external perturbations. Specifically, we aimed to determine how altering anatomical stability by slightly flexing the knee (approximately 15°) or significantly lowering the COM height through knee flexion (approximately 65°) affects postural stability and balance recovery. This study hypothesized that the suspensory strategy with knee flexion would influence balance recovery from external perturbations and that a lightly flexed knee would lead to a shorter COM response time after perturbation compared to a deeply flexed knee with lower COM height.

3.2 Methods

3.2.1 Participants

Sample size was calculated with the F test using G*Power (3.1.9.7); a minimum of 12 participants was required for the present study, with an effect size of $f = 0.4$, $\alpha = 0.05$, and power = 0.8 (Cohen, 2013; Faul et al., 2007). Eighteen healthy young adults (10 male

and 8 female, mean age $\pm$ SD: 24.4 ± 2.2 years, age range: 21–30 years, body mass: 62 ± 13.9 kg, body height: 168.8 ± 5.3 cm) were recruited for this study. Participants with any current or history of orthopedic or neurological diseases were excluded. Before inclusion, the participants were given information regarding the study and signed an informed consent form. This study was approved by the review board of the Faculty of Health Sciences at Hokkaido University (approval number:22–66) and was conducted in accordance with the principles of the Declaration of Helsinki.

3.2.2 Equipment

A perturbation generator was used to move a wooden platform ($74 \times 74 \times 10$ cm) linearly (Hasegawa et al., 2021). A safety harness prevented the participants from falling during the experiment and had no effect on any joint motion (Figure 7). After donning the safety harness and setting reflective markers, the participants were asked to stand barefoot on the platform. They were instructed to position their feet shoulder-width apart and point their toes outward at a 20° angle. Participants were asked to fix their gaze on a circle point in front of them (approximately 1 m away from eye level). Another examiner was positioned near each participant as a safety precaution.

3.2.3 Protocols

A total of nine blocks of perturbations were conducted, combining three perturbation

velocities with three knee angles in a randomized sequence, such that each block focused on one velocity and one knee angle. Each block comprised four trials in each lateral direction (left and right) with a total of eight trials per block. The three perturbation velocities were categorized as low (7 cm/s), mid (15 cm/s), and high (20 cm/s), and the movement distance remained constant at 6 cm (Batair et al., 2018). To manipulate the suspensory strategy, participants were instructed to adopt three different knee angles with 0°, 15°, and 65° of knee flexion. No specific instructions were given regarding other joints. Participants practiced the postures beforehand and received feedback from the examiners to correct any errors during the trials. During the data processing, the participants' knee joint angles and COM height were verified to ensure compliance with the experimental design. The participants were instructed to maintain their balance without taking steps or falling during perturbations. Furthermore, to minimize any potential impact of participants' anticipation or prediction on the experimental outcomes, the eight trials within each block (including the direction) were randomized. MATLAB (MATLAB 2022b, The MathWorks, Inc., Natick, MA, USA) random code was employed to generate the randomization of blocks 1 to 9 and trials 1 to 8. In addition, perturbations were started randomly within 0–10 s of the setup. The data collection for this study on human kinematics was consistent with Study 1, including the collection equipment, software, and body marker configuration.

3.2.4 Data processing

Kinematic analyses, including joint angles, movement of the lateral malleolus, and COM, were performed using Visual3D software (version 6, C-Motion, Inc., Germantown, MD, USA) and processed using MATLAB (Ishida et al., 2014; Taniguchi et al., 2022). Marker trajectory data were low-pass filtered with a zero-lag, fourth-order Butterworth filter with a cut-off frequency of 10 Hz. The knee joint angle was calculated with a joint coordinate system. The COM position of the whole body was calculated from the COM position of each segment that was estimated based on previous reports (de Leva, 1996; Kasahara et al., 2015). The standing stability response to external perturbations was assessed using body COM measurements. To standardize the data, the starting point of the external perturbation (perturbation onset) was defined as the time at which the surface started to move in the forward direction, and the direction of movement of the perturbation generator was characterized as positive (Figure 7a). The baseline interval was defined as the mean value in the interval between the onset of the perturbation and 1,000 ms before the perturbation onset, and this value was recalculated and standardized to zero. COM reaction was defined as the first time point when the COM velocity exceeded five SDs above the baseline velocity continuously for at least 500 ms, and the COM offset represented the first time point when the COM velocity was continuously within five SDs of the baseline velocity for more than 500 ms after COM reaction (Kasahara et al., 2015; Zhu et al., 2022). The reaction time was measured as the time

between the onset of perturbation and COM reaction (Figure 7b). Furthermore, COM peak displacement referred to the maximum displacement of the COM following the perturbation. COM peak time was defined as the time taken by COM peak displacement relative to COM reaction time. COM reversal times were referred to as the intervals between COM peak time and COM offset time. COM reversal time represented the duration between the moments when the COM reached its peak displacement and when it returned to its baseline or reference position (Figure 7b). This measurement was used to determine the distance between the lateral malleolus representing the edge of the base of the support and the extrapolated COM position in the frontal plane (Hof et al., 2005; Hof & Duysens, 2013). The minimum value of the margin of stability (minimum-MOS) between COM reaction and offset was used as an indicator of stability (Figure 7c).

To avoid the effects of the first trial response (Allum et al., 2011), the data from the initial trial for each direction of each block were excluded (i.e., 2 trials were excluded in each block). The average of the six values for each participant was calculated. An additional assessment of standing stability was performed using a MOS calculation.

3.2.5 Statistical Analysis

All statistical analyses were performed using SPSS Statistics (version 18.0; IBM Corp., Armonk, NY, USA). The quantile-quantile plot and Shapiro–Wilk test were conducted

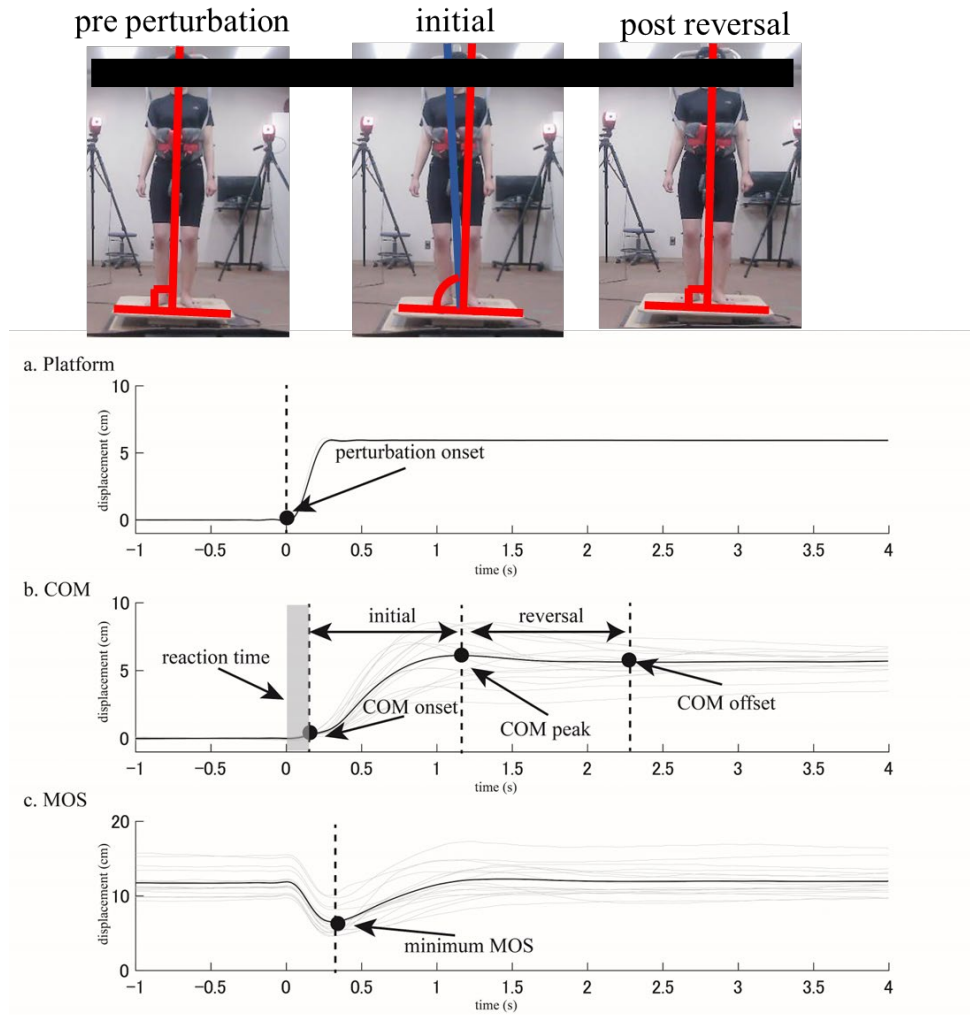


Figure 7. Raw data samples from all experiments.

The top images show a participant standing on the perturbation generator and wearing a safety harness. During pre-perturbation, the subject stood in a posture roughly perpendicular to the perturbation generator. During the initial phase after the perturbation, the subject's body was tilted, and the blue line was used as a reference. After the reversal phase, the body of the participant returned to a perpendicular relationship with the perturbation device. The following three images represent the displacement conditions of the perturbation generator (platform), COM, and MOS. The y-axis represents the amplitude of displacement in centimeters, while the x-axis represents time in seconds. The gray lines indicate the data of a single participant, while the black lines represent the average of all participants. (a) The movement trajectory of the wooden platform. (b) The movement trajectory of the COM in the sagittal plane. (c) The movement trajectory of the MOS. COM, center of mass; MOS, margin of stability.

to test normality. Two-way repeated-measures analysis of variance (ANOVA) was used to examine the effects of perturbation velocity (three velocities) and knee angle (three different degrees of knee flexion) on the outcome measure. Sphericity assumptions were evaluated using Mauchly's test, and if violations were detected, the Greenhouse-Geisser correction was applied for adjustment. A Bonferroni post-hoc analysis was conducted using the pairwise comparisons method. The effect size was calculated using partial eta squared values (η^2) (Cohen, 2013). The significance level was set at $P < 0.05$.

3.3 Results

No significant interaction effect (perturbation velocity $\times$ knee angle) was observed on COM height; however, there was a significant main effect of knee angle on COM height ($P < 0.001$). Post-hoc tests showed that the COM height was the highest at 0° knee flexion and the lowest at 65° knee flexion ($P < 0.001$) (Table 2, Figure 8a).

For COM reaction time, ANOVA demonstrated significant effects of perturbation velocity and knee angle (respectively, $P < 0.001$), with no significant interaction effect (Table 2). Further pairwise comparisons revealed a significant difference in COM reaction time between the low velocity condition and the mid or high velocity conditions ($P < 0.001$) (Table 2). Post hoc tests revealed a significant difference in COM reaction time between 65° knee flexion and 0° or 15° knee flexion ($P < 0.05$) (Table 2, Figure 8b).

There was no significant interaction or main effect of perturbation velocity and knee

	Knee flexion angle				two-way ANOVA			
	Vel.	0°	15°*	65°*#	fixed factor	F value	P value	η ²
COM height (%)	Low	55.28 ± 0.64	54.28 ± 0.78	47.14 ± 1.98	P. velocities	24.578	0.000	0.591
	Mid	55.26 ± 0.69	54.28 ± 0.83	45.96 ± 2.80	Knee angles	12.211	0.000	0.418
	High	55.27 ± 0.69	54.49 ± 0.77	46.55 ± 2.09	Interaction	1.048	0.389	0.058
	Vel.	0°	15°	65°*#	fixed factor	F value	P value	η ²
COM reaction time (s)	Low	0.15 ± 0.06	0.17 ± 0.07	0.21 ± 0.06	P. velocities	24.578	0.000	0.591
	Mid†	0.08 ± 0.04	0.11 ± 0.05	0.15 ± 0.06	Knee angles	12.211	0.000	0.418
	High†	0.09 ± 0.07	0.09 ± 0.07	0.13 ± 0.08	Interaction	1.048	0.389	0.058
	Vel.	0°	15°	65°	fixed factor	F value	P value	η ²
COM peak time (s)	Low	1.43 ± 0.28	1.36 ± 0.27	1.35 ± 0.29	P. velocities	3.073	0.081	0.153
	Mid	1.29 ± 0.50	1.23 ± 0.32	1.15 ± 0.26	Knee angles	1.935	0.170	0.102
	High	1.29 ± 0.32	1.30 ± 0.30	1.25 ± 0.24	Interaction	0.323	0.821	0.019
	Vel.	0°	15°	65°	fixed factor	F value	P value	η ²
COM peak amplitude (cm)	Low	6.69 ± 0.84	6.34 ± 0.98	6.76 ± 0.86	P. velocities	2.463	0.100	0.127
	Mid	6.35 ± 1.22	6.15 ± 1.27	6.04 ± 1.47	Knee angles	2.537	0.094	0.130
	High	6.48 ± 1.54	5.91 ± 1.52	6.47 ± 1.43	Interaction	1.691	0.190	0.090
	Vel.	0°	15°	65°*#	fixed factor	F value	P value	η ²
minimum-MOS (cm)	Low	8.97 ± 2.25	8.95 ± 2.24	8.31 ± 1.93	P. velocities	80.808	0.000	0.826
	Mid†	7.42 ± 1.91	7.39 ± 1.90	6.86 ± 1.69	Knee angles	7.854	0.002	0.316
	High†	7.70 ± 2.00	7.33 ± 2.13	6.50 ± 1.52	Interaction	0.784	0.549	0.044
	Vel.	0°	15°*	65°*#	fixed factor	F value	P value	η ²
COM reversal time (s)	Low	0.87 ± 0.42	0.64 ± 0.31	0.33 ± 0.31	P. velocities	2.972	0.067	0.147
	Mid	0.79 ± 0.41	0.48 ± 0.38	0.33 ± 0.33	Knee angles	36.020	0.000	0.679
	High	0.73 ± 0.51	0.46 ± 0.42	0.25 ± 0.29	Interaction	0.453	0.770	0.026
	Vel.	0°	15°*	65°*#	fixed factor	F value	P value	η ²

Table 2. The results for each outcome measure. * $P < 0.05$ compared with 0° knee flexion; # $P < 0.05$ compared with 15° knee flexion; † $P < 0.05$ compared with low velocity. COM, center of mass; minimum-MOS, minimum value of the margin of stability; vel, velocity; P. velocities, perturbation velocities; SD, standard deviation; ANOVA, analysis of variance; η², the partial eta squared value.

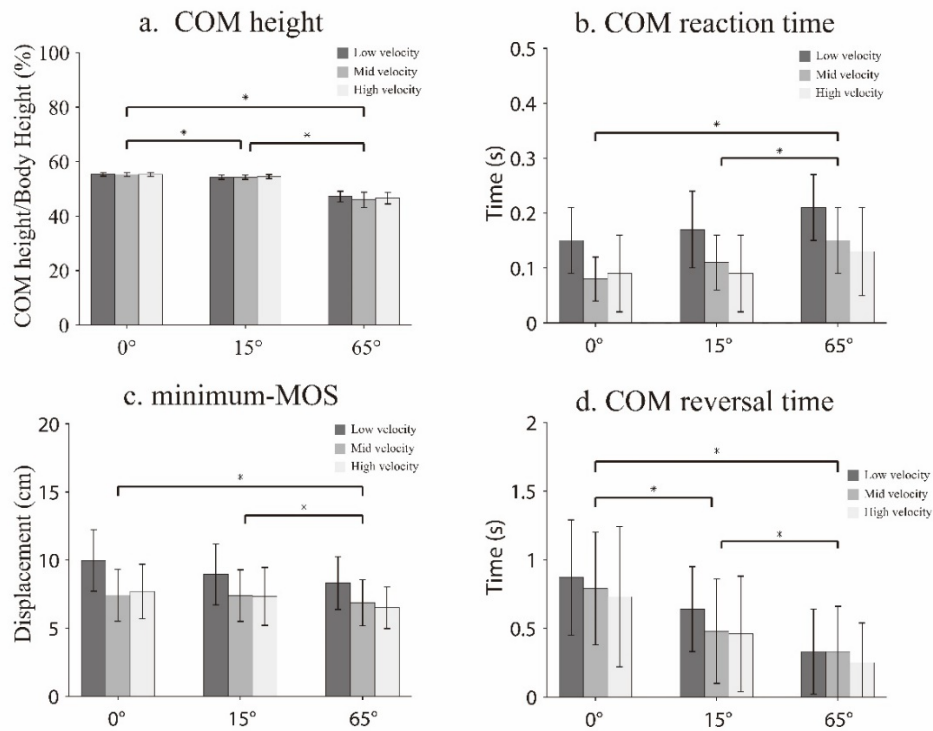


Figure 8. Comparison of measurements between 0°, 15°, and 65° of knee flexion at low, mid, and high velocities. (a) The COM height, with the y-axis indicating COM height/body height in % and the x-axis indicating the 0°, 15°, and 65° knee flexion. (b) The COM reaction time, with the y-axis indicating time in seconds and the x-axis indicating the 0°, 15°, and 65° knee flexion. (c) The minimum-MOS, with the y-axis indicating the distance in centimeters and the x-axis indicating the 0°, 15°, and 65° knee flexion. (d) COM reversal time, with the y-axis indicating time in seconds and the x-axis indicating 0°, 15°, and 65° knee flexion. * indicates $p < 0.05$. COM, center of mass; minimum-MOS, minimum value of the margin of stability.

angle on peak time and amplitude (Table 2). Minimum-MOSs were observed in all participants during the initial phase between the perturbation onset and COM peak time. ANOVA revealed significant main effects of velocity and knee angle ($P < 0.05$) but no significant interaction effect (Table 2). The pairwise comparisons revealed a significant difference in Minimum-MOS between the low velocity condition and the mid or high

velocity conditions ($P < 0.001$). There was a significant difference in minimum-MOS between the 65° knee flexion and 0° or 15° knee flexion ($P < 0.05$) (Table 2, Figure 8c).

For COM reversal time, ANOVA showed significant main effects of knee angle ($P < 0.001$), but not for perturbation velocities or their interaction effect (Table 2). Post hoc tests showed that COM reversal time with a 65° knee flexion was significantly shorter than that with a 0° knee flexion ($P < 0.05$) (Table 2). Post hoc tests showed that COM reversal time with a 65° knee flexion was significantly shorter than that with 0° and 15° knee flexions ($P < 0.05$) (Table 2, Fig. 8d). Moreover, COM reversal time with a 15° knee flexion was significantly shorter than that with a 0° knee flexion ($P < 0.05$) (Table 2, Figure 8d).

3.4 Discussion

Two important roles of the knee in postural control are controlling the height of the COM (Kasahara et al., 2015; Oude Nijhuis et al., 2007) and absorbing external perturbations (Di Giulio et al., 2013; Kim et al., 2017). Previous studies have shown that the knee plays a crucial role in absorbing sudden lateral tilts (Allum et al., 2003; Carpenter et al., 1999; Oude Nijhuis et al., 2007). When the knee does not respond appropriately, the motion of the support surface is transmitted directly to the pelvis, which leads to lateral instability (Küng et al., 2009). The ability of the knee to absorb impact contributes to a reduced trunk tilt (Oude Nijhuis et al., 2007) and slower COM

reaction times. In this study, at lower and mid-velocities, the extended reaction times of the COM in the larger degree of knee flexion may be due to the initial impact being absorbed by the knee motion. Another possible explanation is the change in stiffness of the body segments due to knee flexion, which increases the mobility of the knee joint and results in lower stiffness and longer reaction times (Kasahara et al., 2015; Kim et al., 2015; Oude Nijhuis et al., 2007).

Generally, a higher stiffness allows for more efficient force transfer between segments (Cenciarini et al., 2010; Loram & Lakie, 2002). Although a lower COM height may provide some balance advantages (Kasahara et al., 2015), excessive knee flexion associated with a lower COM height can result in the excessive absorption of lateral perturbation energy (Lam et al., 2016). This results in the absorption and dispersion of energy within the knee joint, which in turn reduces the ability of the knee to transmit or dissipate energy quickly, ultimately leading to decreased balance.

Some studies believe that smaller displacements and shorter COM peak time indicate better balance ability and a lower risk of falling (Chen et al., 2014; Ma & Lee, 2017). In this study, most of the COM peaks were observed after the cessation of platform motion, and the peak amplitudes did not vary among the different knee angles at each velocity. The perturbation velocity used in this study varied, but the displacement was fixed at approximately 6 cm. However, as the perturbation intensity used in this study was below the threshold required to induce a step response (Batcir et al., 2018), large COM

displacements may not have been produced after the termination of platform motion. Further studies using various platform motion parameters are necessary to fully understand the benefits of this postural strategy on inertial forces.

This work also revealed that a greater degree of knee flexion along with a lower COM resulted in a lower minimum-MOS. This suggests that an excessively low COM may negatively impact postural control. According to Hof et al. (2005), the MOS is inversely proportional to the COM height and velocity. The perturbation in our study originated from the ground, causing the COM velocity after the perturbation to be directed away from the supporting foot. Hence, a lower COM height may result in a smaller MOS and increase the risk of falls. Furthermore, in a deep squat, the ankle motion is significantly limited in the lateral direction due to the position of the trochlea of the talus. Studies have also found that the COP shifts more rearward during deep squats compared to upright standing, with small functional stability limits (Sugama et al., 2020), indicating that excessively deep squats are unstable (Jebelli et al., 2016; Sugama et al., 2020). Based on our findings, it is recommended to maintain a slight degree of knee flexion for postural stability during the initial phase of sudden perturbation, rather than a larger degree of knee flexion or a lower COM height.

The restoration of balance following external perturbations is crucial and can be achieved by modifying the position of the center of mass (COM) with respect to the base of the support, either with or without compensatory stepping and/or grabbing a nearby

support (Pai & Patton, 1997; Rogers et al., 2021). The results of this study indicate that a larger degree of knee flexion shortens the time it takes to return to the original COM position, suggesting that it is beneficial in quickly restoring balance stability following a perturbation. The reversal time is considered an overall balance ability and the ability of the central nervous system to integrate sensory information. The muscles' ability to produce the appropriate torque can contribute to faster completion of the phase (Ma & Lee, 2017; Sienko et al., 2012). Additionally, postural muscles of the lower limbs in the flexed knee condition (i.e., squatting posture) are activated more than in the full extension condition at baseline, meaning they can reach the required muscle activity level more quickly. Knee flexion may also improve motor sensitivity during postural control and movement information processing during the reversal phase (Jiang et al., 2023). However, excessive flexion may lead to buckling of the knee or hip joint in older adults with muscle weakness (Kasahara & Saito, 2021). In conclusion, light knee flexion is recommended for balance recovery from external perturbations.

Based on the results of this study, it can be concluded that a knee that is lightly flexed presents more difficulty in maintaining balance during the early phase of lateral perturbations but offers beneficial effects during the reversal phase. These findings help to clarify the relationship between the COM height and balance, but more research is needed to confirm these results.

Chapter 4

Third Study

**Visualizing the Suspensory Strategy and
Elucidating its Complexity through Principal
Component Analysis**

4.1 Introduction

One of the reasons for not adding researchers' interest on the suspensory postural strategy is that the knee motion is very small during the postural control in the static standing posture (Rung et al., 1999; Kasahara et al., 2015). Another reason is that the maintenance of knee joint flexion in daily activities is considered as an abnormal state (de Groot et al., 2014; Balzini et al., 2003). Although postural strategies are conveniently divided into several types, no knee strategy has been mentioned from these reasons. However, small knee motions and associated moments have often been observed in data regarding the postural balance control (Rung et al., 1999; Kasahara et al., 2015; Cheng, 2016). This implies that the very small knee motion has some role in the postural control, for example, the coordination among lower limb joints.

Although most conventional movement analyses focused on specific aspects of each joint motion, such analyses often neglect important information about segment interactions (Haid et al., 2019). Recently, regardless of the amplitude of the joint motion, several principal component analyses (PCA) are developed in kinematic data analysis to determine relevant aspects of a motion in an unbiased and data driven way (Haid et al., 2018 and 2019). The advantage of PCA is to be able to reduce data complexity without neglecting segment interactions and the PCA can characterize and compare the amount of contribution of each individual postural strategy (Haid et al., 2019). Furthermore, Haid's study (2018) used principal component analysis (PCA) computations as well as

principal movement extracted techniques to address this issue and extracted single joint strategy that can be observed in video data.

The objectives of this study were two-fold: 1. PCA and principal movement extraction were employed to deconstruct the full body movement under different knee flexion angle standing postures and to visualize joint strategies, with a particular focus on analyzing whether the suspensory strategy for knee flexion-extension or vertical direction posture control exists in the flexed knee posture. 2. The complexity of the full-body movement under different standing postures was explored by analyzing the variation for each subject. Based on prior research, this study hypothesized that flexed knees may exhibit vertical posture control on major components (Hypothesis 1: H1) and that whole-body posture movement complexity is lower in knee flexion standing postures (Hypothesis 2: H2).

4.2 Methods

4.2.1 Participants

Nineteen healthy young adults (11 males and 8 females; mean age $\pm$ SD, 24.3 $\pm$ 2.2 years; age range, 21–30 years; weight, 62.7 $\pm$ 13.8 kg; and height, 169.5 $\pm$ 5.9 cm) were enrolled in this study. The participants with any current or past orthopedic or neurological illnesses were excluded from the study. Prior to inclusion, the participants were informed about the study, and they signed a consent form for participation in this study. Consequently, all the participants were enrolled in this study. This study was approved by the review board

of our institution (22–66) and was conducted in accordance with the ethical guidelines set forth by the 1964 Declaration of Helsinki.

4.2.2 Equipment and Procedures

The experimental conditions of this study, as well as data collection and preprocessing, were the same as those in Study 1. Please refer to Study 1 for further details. In this phase, we collected data from 35 full marker data in three different postures of standing each at knee flexion 0°, 15°, and 65°.

4.2.3 Data processing

This study analyzed the data between the 10th to 30th second after the data were recorded to ensure the stability of the marker data. The COM sway amplitudes in the AP, ML, and vertical directions were calculated at the selected analysis intervals and normalized according to the height of each participant. The COM height was calculated as the average COM height at the selected analysis intervals and normalized to the height of each participant (Kasahara et al., 2015).

This study referred to Haid's study and analyzed full-body kinematic data over a selected 20 seconds (Haid et al., 2019). To exclude the arm data from visually interfering with the torso data, this study removed marker data (four markers) on the elbow and wrist joints before performing the data analysis, so that there were ultimately 31 marker data.

The marker position was normalized by dividing it by the height of each participant. We then processed the data using a PManalyzer software developed by Haid (2019) as follows. The datasets from all subjects were concatenated to create a 31 marker (excluding the marker in the double upper extremity to reduce visual interference) $\times$ 3-dimensional matrix, with 200 Hz recordings of 20 s duration for 19 subjects. After normalizing and concatenating the data from all participants and trials, PCA was performed using a PManalyzer on the dataset to calculate eigenvectors (PC_k (principal component) where k indicates the order of the eigenvectors (EV)), which describe linear patterns of correlated marker motion. This software also recalculated the new positions of the markers under each principal component using the principal component scores and other values. The time-series marker positions were presented as principal movements (PM_k) in the video data, which were used as part of the qualitative analysis. In addition, the software determined the relative variance rVAR_k of each PM_k to the subject's overall postural variance from the principal component scores. The rVAR_k values are then summed to calculate the cumulative relative variance (rCUM_k), which represents the dimensionality of the movement and can be used as a measure of coordination complexity (Haid et al., 2018).

4.2.4 Interpreting Video Data

Based on prior research and textbooks for balance-related lower extremity strategies,

these joint strategies were defined in this study using explicit language to facilitate the co-researcher's judgment of joint strategies in the video data: Ankle Joint Strategy: Utilizing ankle joint movement to maintain balance control; Hip Joint Strategy: Primarily employing hip joint movements for balance control; and Mixed Strategy: Employing two or more lower-limb joint strategies to control postural (Nakamura & Nagasaki, 2016; Houghlum & Bertoti, 2012; Haid et al., 2018; Wachholz et al., 2019).

This study focused on whether there is a suspensory strategy for knee flexion that may affect postural control. Therefore, this study temporarily named the strategy of controlling the vertical direction of the COM through knee flexion-extension as the knee strategy based on the definition of the joint strategies mentioned above, as well as to ensure the unity of naming the joint strategies. The specific definitions are as follows: Knee Joint Strategy: Achieving balance control through flexion or extension of the knee joint.

Following the identification of joint strategies, an assessment was conducted to determine the predominant directors of movement, including the AP, ML, and vertical directions. Through assessments by two experts in the field of postural control, video data were evaluated using a structured questionnaire (Figure 9) to confirm the joint strategies and predominant movement directions associated with each strategy

Please fill in the table below about the lower limb joint strategies and the corresponding movement directions observed in the video.

- Joint strategies: 1. Ankle joint strategy; 2. Knee joint strategy; 3. Hip joint strategy; 4. mixed lower-limb joint strategy, and 5. Unable to identify.
- Dominant movement directions: 1. Anterior-posterior; 2. Left-right; 3. Vertical; 4. Unable to identify.

Video number	Joint strategies	Movement directions
1		
2		
...		
15		

Figure 9. Questionnaire for qualitative description of video data.

(Robinovitch et al., 2013). Assessing consistency enhances the reproducibility of the study and ensures reliability of the qualitative results (Robinovitch et al., 2013).

4.3 Statistics

Shapiro–Wilk tests were used to determine whether rVARk and rCUMk fit a normal distribution. Friedman’s test was used to examine the effects of posture (three different degrees of knee flexion). Post-hoc analyses between the two postures with different knee flexions were conducted using pairwise comparisons. The significance level was set at a P-value < 0.05.

4.4 Results

The first five PMs (PM1-PM5) described more than 90% of the total movement variance during the three postures (Table4). The qualitative interpretation of the joint

PM	0°			15°			65°		
	Joint strategy	Direction	EV%	Joint strategy	Direction	EV%	Joint strategy	Direction	EV%
1	ankle	AP	58.75	ankle	AP	47.24	mixed	AP	52.13
2	ankle	ML	25.36	ankle	ML	34.07	knee	vertical	24.99
3	hip	AP	5.69	knee	vertical	6.56	ankle	ML	6.45
4	hip	ML	2.20	/	/	3.01	/	/	5.46
5	/	/	1.29	/	/	2.30	ankle	AP	3.92

Table 4. Joint strategies and main movement directions of the first five PMs. EV, eigenvectors; PM, principal movement; AP, Anterior-posterior; ML, Medial-lateral.

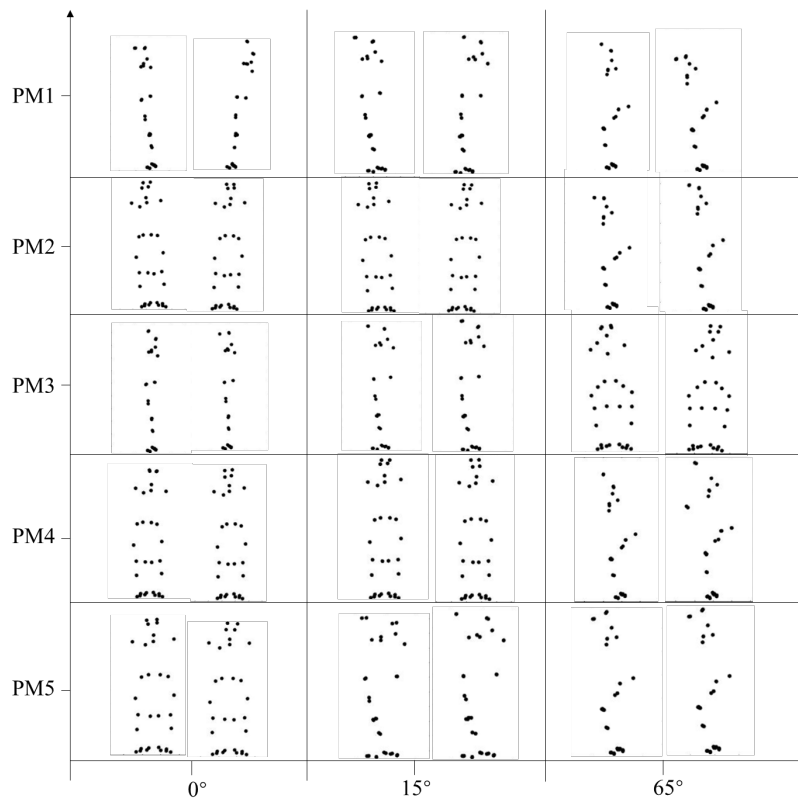


Figure 10. Visualization of principal movement 1–principal movement 5 of the three postures with amplification 10 factors.

strategies and movement directions of PM1–PM5 was quantified through posture control

strategies and directions determined by three researchers. In the standing position with knee flexion of 0°, the ankle and hip strategies dominated the main movements, and vertical movement was not observed. When knee flexion was 15°, only the ankle and knee strategies were observed in the main movement components, and the knee strategy dominated mainly in the vertical direction movement with a contribution of (6.56%) to the full movement components. When the knee flexion was 65°, there was a mixture of the ankle and knee strategy, knee strategy, and ankle strategy, where the knee strategy also dominated the vertical direction movement and its contribution was (24.99%) (Table4). Video screenshots of the joint strategy visualization for each posture are shown in Figure 10.

Tables 4 and 5 present the statistical results for rVARk and rCUM across the three postures on PM1–PM5, respectively. No significant variations were observed between

	X2	DOF	P	Post-Hoc between postures		
				0°-15°	15°-65°	0°-65°
rVAR1	2.947	2	0.229	/	/	/
rVAR2	0.947	2	0.623	/	/	/
rVAR3	4.526	2	0.104	/	/	/
rVAR4	7.053	2	0.029	0.223	0.028*	1.000
rVAR5	0.737	2	0.692	/	/	/

Table 5. Statistical results for the effects of knee flexion on the relative cumulative variance rVARk based on Friedmann tests. * indicates significant effects on the relative variance of the movement components. DOF, degree of freedom.

	X2	DOF	P	Post-Hoc between postures		
				0°-15°	15°-65°	0°-65°
rCUM1	2.947	2	0.229	/	/	/
rCUM2	2.000	2	0.368	/	/	/
rCUM3	2.211	2	0.331	/	/	/
rCUM4	0.316	2	0.854	/	/	/
rCUM5	0.316	2	0.854	/	/	/

Table 6. Statistical results for the effects of knee flexion on the relative cumulative variance rCUMk based on Friedmann tests. DOF, degree of freedom.

the three knee flexion angles during rVAR1, rVAR2, rVAR3, and rVAR5. While only rVAR4 exhibited a significant difference between knee flexions of 15° and 65°, its contribution to the overall motion in PM4 was limited to 2.2%-5.5%. This indicated that movement complexity did not show significant differences between postures.

4.5 Discussion

In a study by Wachholz (2019), full body movement during static standing was calculated using PCA, and it was observed that the first five PM were the ankle (AP), ankle (ML), hip (AP), breathing, and upper body rotation. In this study, the first three PM (i.e., postural strategy) in the standing posture confirmed by the three researchers in the field of postural control were consistent with those reported in a previous study

(Wachholz et al., 2019), and the fourth and fifth principal movement reported in the present study were slightly different from those reported in a previous study. The fourth PM is the hip strategy and has ML direction movement, and we mainly focus on joint strategies; therefore, this study did not find other body movements, such as breathing. Interestingly, this part of the study further supports the description of ankle and hip strategies exist in a prior study, the single or double inverted pendulum model was employed by previous studies (Winter, 1995; Rung et al., 1999; Cheng, 2016) could be observed more clearly in the various principal movement in this study.

Previous studies have observed that some subjects use knee flexion-extension to absorb external perturbations or lower their COM to achieve better posterior directional balance (Di Giulio et al., 2013; Kasahara et al., 2015). Although there is a large body of research supporting the non-direct evidence that knee joint movement may be critical for balance control, because the knee joints move at a relatively small angle ($<5^\circ$) in most static balance controls, there is no evidence directly suggesting a role for the knee joint in balance control to our knowledge (Cheng et al., 2016; Kasahara et al., 2015; Rung et al., 1999). The present study builds on this by using PCA to confirm that, in a stance with knee flexion, the suspensory strategy that accompanies knee flexion and extension also plays a very important role in overall balance control (6%-24% contribution). In this study, we show, for the first time, the effect of knee flexion-extension on postural control in the vertical direction of the COM in static standing postures, as described by Nashner and

McCollum (1985).

Based on the descriptions of rVAR and rCUM from prior studies (Haid et al., 2019; Wachholz et al., 2019), the results of this study only presented that PM4 at 65° of knee flexion explains a greater VAR relative to a standing posture with 15° of knee flexion, which, although suggests that 15° of knee flexion, it appears to be more complex in PM4 during knee flexion 65°. However, when considered no joint strategies were observed in PM4 by video data, this principal movement did not appear to be related to balance balance-related joint strategies and did not account for a large proportion of the full movement. Although the present study did not directly explore principal movements outside of joint strategies, this alteration of PM4 may be an alteration of the principal movement related to breath movements as described in Wachholz et al. (2019), which can find some evidence in Holmes et al. (2016) on tai chi, as that study found that after a period of time related to the tai chi exercises related to knee movements, the coupling between breath and standing balance control was altered. Therefore, the data may indicate that a standing posture with knee flexion alters the complexity of other movements that not related the balance control.

The data on whole-body posture movement complexity did not support the H2 that whole-body posture movement complexity is lower in knee flexion postures. Haid's earlier study found that COP movements formed through whole-body musculoskeletal activity were consistent with whole-body movement complexity. However, Wachholz

(2019) also found that changes in balance-related or motor-related sensory input can lead to alterations in an individual's motor regularity (sample entropy), which is also supported by the results of Study 1 as well as other research (Haid et al., 2018), and such changes in motor regularity may not require the incorporation of additional coordinative complexity, meaning that the changes of movement complexity will not be required. On the other hand, the present study found that although no significant difference was demonstrated in coordinative complexity, the content of the main movements changed, and the postural control brought about by flexion and extension of the knee joint gradually increased its contribution to the movements to 6.56%-24.99% as the knee flexion angle increased. In addition, no hip strategy was observed in the first five principal movements. Therefore, these results may indicate that the knee strategy replaced the hip strategy for balance control when standing with knee flexion. However, this study could not explain how vertical movement control replaced horizontally oriented balance control.

4.6 conclusion

The present study visualized the draping strategy for the first time through the extraction of motor components and further demonstrated the presence of this strategy in the flexed knee state and the potential for improved balance control. However, further research is still needed to confirm whether the draping strategy can play a role in rehabilitation and whether it can be observed in dynamic balance during major

movements.

Chapter 5

Summaries

5.1 Aim and Goals

The primary aim of this study was to investigate whether flexion of the knee joint has a beneficial effect on balance control, and to explore the observability of a suspensory strategy with knee flexion under specific conditions.

5.2 Summaries

5.2.1 Suspensory Strategy and Static Balance Control

In the first study, it was observed that when the knee joint was flexed, the range of COM movement increased in the anterior-posterior, medial-lateral, and vertical directions. Coupled with the changed overall sensory integration and decreased sample entropy, we hypothesize that the suspensory strategy is a compensatory strategy. The enhanced range of COM movement within a safe zone may strengthen the sensory integration and result in more regularized COM movements, suggesting a potentially advantageous compensatory mechanism for balance control.

5.2.2 Suspensory Strategy and Dynamical Balance Control

For dynamic balance control, perturbations of varying magnitudes were applied to investigate the balance control under different knee flexion states. Excessive knee flexion was found to induce a delay in the perturbation response time, and smaller minimum-MOS. However, superior balance performance in the squatting position during the recovery phase, supported by reversal time data, suggests that the suspensory strategy associated with knee flexion may have beneficial for balance control without eliciting

stepping reactions under non-stepping disturbance conditions.

5.2.3 Visualizing Suspensory Strategy

This phase aims to confirm the observability of the suspensory strategy (vertical COM control through knee flexion-extension) through data processing. Regardless of mild knee flexion or deep squatting (knee flexion 65°), vertical COM movement was observed in major PM. In contrast to data from previous research focusing on whole-body motion complexity (COM), motion data from whole-body markers did not exhibit paradoxical complexity. This result suggests that changes in joint strategies may not observed in whole-body movement complexity but are reflected in the COM movement complexity.

Chapter 6

Limitation

This thesis had several limitations. First, the dissertation sample included only healthy young adults, which limits the generalizability of the findings to other age groups and populations with balance impairments. Second, this study focused only on balance in the feet-at-shoulder-width standing position under eye-open conditions, which may not provide a comprehensive representation of balance performance in different environments. Electromyography data were not collected in this study, and support from these data may be required for a more detailed analysis of conclusions or muscle contributions. In terms of knee flexion angles, this study examined three specific knee flexion angles (0°, 15°, and 65°), but did not include the intermediate angle between 15° and 65°. Finally, for the principal component analysis aspect of suspensory strategy, only subjective reports from the three researchers were provided in terms of joint strategy determination, and no quantitative reports were provided.

Chapter 7

Future prospects

This thesis comprehensively explored the significance of suspensory strategy with knee flexion in both static and dynamic balance control and demonstrated that this strategy is effective. However, as highlighted in the study's limitations, future research should delve into the role and impact of this strategy across different age groups and individuals with balance impairment. While our analysis of balance orientation and postural control utilized whole-body kinematic data based on prior research, further investigations are warranted to probe central and muscular activities during the execution of the hanging strategy. Collecting additional data, such as electroencephalography (EEG) and electromyography (EMG), during the execution of the hanging strategy could offer deeper insights into the neural and muscular dynamics involved.

In the realm of balance-related rehabilitation, beyond focusing on patients' strategies at the ankle and hip joints, there is a need to explore their abilities for vertical postural control. The suspensory strategy not only compensates for the reduced sensory function in individuals with balance impairments, but also enhances balance functionality under perturbation conditions. For musculoskeletal rehabilitation programs, references can be made to existing practices, such as squat training or Tai Chi. These training modalities may potentially provide further theoretical insights into balance training. In conclusion, future studies should address the gaps outlined in this research, investigating the suspensory strategy's applicability across diverse demographics and its impact on individuals with balance impairments. Additionally, exploring neural and muscular

dynamics during the execution of this strategy and expanding research into vertical balance control can contribute to the development of more targeted and effective rehabilitation strategies.

Chapter 8

General Conclusion

This thesis, encompassing both static and dynamic balance assessments, revealed that adopting a flexed knee posture enhances sensory integration and induces a shift in central control patterns, leading to a more regularized postural control mechanism during static balance. In the context of dynamic balance, the findings demonstrate that while a flexed knee posture reduces the recovery time following perturbations, excessive flexion of the knee (65°) may bring the COM dangerously close to the edge of the base of support, resulting in a potential risk of falling during perturbations.

Moreover, despite the relatively modest range of knee motion during balance control, the PCA results highlight the significant role of the suspensory strategy with knee flexion in postural control (contributing 6-24%). Consequently, this study underscores the specific triggering of suspensory strategy in certain postures and its advantageous impact on both static and dynamic balance when accompanied by slight knee flexion.

References

- Adkin, A. L., & Carpenter, M. G. (2018). New Insights on Emotional Contributions to Human Postural Control. *Frontiers in neurology*, 9, 789.
<https://doi.org/10.3389/fneur.2018.00789>
- Alia A. Alghwiri, Susan L. Whitney., (2012), CHAPTER 18 - Balance and falls,
Editor(s): ANDREW A. GUCCIONE, RITA A. WONG, DALE AVERS,
Geriatric Physical Therapy (Third Edition), Mosby, Pages 331-353, ISBN
9780323029483, <https://doi.org/10.1016/B978-0-323-02948-3.00027-4>.
- Allum, J. H., Carpenter, M. G., & Honegger, F. (2003). Directional aspects of balance corrections in man. *IEEE engineering in medicine and biology magazine: the quarterly magazine of the Engineering in Medicine & Biology Society*, 22(2), 37–47. <https://doi.org/10.1109/MEMB.2003.1195694>
- Allum, J. H., Tang, K. S., Carpenter, M. G., Oude Nijhuis, L. B., & Bloem, B. R. (2011). Review of first trial responses in balance control: Influence of vestibular loss and Parkinson's disease. *Human movement science*, 30(2), 279–295.
<https://doi.org/10.1016/J.HUMOV.2010.11.009>
- Assländer, L., & Peterka, R. J. (2014). Sensory reweighting dynamics in human postural control. *Journal of neurophysiology*, 111(9), 1852–1864.
<https://doi.org/10.1152/jn.00669.2013>
- Bakker, M., Allum, J. H., Visser, J. E., Grüneberg, C., van de Warrenburg, B. P.,

- Kremer, B. H., & Bloem, B. R. (2006). Postural responses to multidirectional stance perturbations in cerebellar ataxia. *Experimental neurology*, 202(1), 21–35.
<https://doi.org/10.1016/j.expneurol.2006.05.008>
- Balzini, L., Vannucchi, L., Benvenuti, F., Benucci, M., Monni, M., Cappozzo, A., & Stanhope, S. J. (2003). Clinical characteristics of flexed posture in elderly women. *Journal of the American Geriatrics Society*, 51(10), 1419–1426.
<https://doi.org/10.1046/j.1532-5415.2003.51460.x>
- Batcir, S., Sharon, H., Shani, G., Levitsky, N., Gimmon, Y., Kurz, I., Shapiro, A., & Melzer, I. (2018). The inter-observer reliability and agreement of lateral balance recovery responses in older and younger adults. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, 40, 39–47.
<https://doi.org/10.1016/J.JELEKIN.2018.03.002>
- Benedetti, M. G., Berti, L., Presti, C., Frizziero, A., & Giannini, S. (2008). Effects of an adapted physical activity program in a group of elderly subjects with flexed posture: clinical and instrumental assessment. *Journal of neuroengineering and rehabilitation*, 5, 32. <https://doi.org/10.1186/1743-0003-5-32>
- Borg, F. G., & Laxåback, G. (2010). Entropy of balance--some recent results. *Journal of neuroengineering and rehabilitation*, 7, 38. <https://doi.org/10.1186/1743-0003-7-38>

- Buchecker, M., Müller, E., Wegenkittl, S., Sattlecker, G., & Stöggl, T. (2018). An entropy approach for evaluating adaptive motor learning processes while walking with unstable footwear. *Human movement science*, 60, 48–56.
<https://doi.org/10.1016/j.humov.2018.05.005>
- Carpenter, M. G., Allum, J. H., & Honegger, F. (1999). Directional sensitivity of stretch reflexes and balance corrections for normal subjects in the roll and pitch planes. *Experimental brain research*, 129(1), 93–113.
<https://doi.org/10.1007/s002210050940>
- Carpenter, M. G., Murnaghan, C. D., & Inglis, J. T. (2010). Shifting the balance: evidence of an exploratory role for postural sway. *Neuroscience*, 171(1), 196–204. <https://doi.org/10.1016/j.neuroscience.2010.08.030>
- Cenciarini, M., Loughlin, P. J., Sparto, P. J., & Redfern, M. S. (2010). Stiffness and damping in postural control increase with age. *IEEE transactions on bio-medical engineering*, 57(2), 267–275. <https://doi.org/10.1109/TBME.2009.2031874>
- Chagdes, J. R., Rietdyk, S., Haddad, J. M., Zelaznik, H. N., Raman, A., Rhea, C. K., & Silver, T. A. (2009). Multiple timescales in postural dynamics associated with vision and a secondary task are revealed by wavelet analysis. *Experimental brain research*, 197(3), 297–310. <https://doi.org/10.1007/s00221-009-1915-1>
- Chen, C. L., Lou, S. Z., Wu, H. W., Wu, S. K., Yeung, K. T., & Su, F. C. (2014). Effects of the type and direction of support surface perturbation on postural responses.

Journal of neuroengineering and rehabilitation, 11, 50.

<https://doi.org/10.1186/1743-0003-11-50>

Cheng, K. B. (2016). Does knee motion contribute to feet-in-place balance recovery?.

Journal of biomechanics, 49(9), 1873–1880.

<https://doi.org/10.1016/j.jbiomech.2016.04.026>

Cheng, K. B., & Yeh, C. K. (2015). A unified approach for revealing multiple balance recovery strategies. *Human movement science*, 44, 307–316.

<https://doi.org/10.1016/j.humov.2015.10.001>

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences* (revised ed.).

Academic Press.

Coventry, E., O'Connor, K. M., Hart, B. A., Earl, J. E., & Ebersole, K. T. (2006). The effect of lower extremity fatigue on shock attenuation during single-leg landing.

Clinical biomechanics (Bristol, Avon), 21(10), 1090–1097.

<https://doi.org/10.1016/j.clinbiomech.2006.07.004>

Damiano, D. L., Wingert, J. R., Stanley, C. J., & Curatalo, L. (2013). Contribution of hip joint proprioception to static and dynamic balance in cerebral palsy: a case control study. *Journal of neuroengineering and rehabilitation*, 10(1), 57.

<https://doi.org/10.1186/1743-0003-10-57>

DeLisa, J. A., Gans, B. M., & Walsh, N. E. (Eds.). (2005). *Physical medicine and rehabilitation: principles and practice (Vol. 1)*. Lippincott Williams & Wilkins.

- Di Giulio, I., Baltzopoulos, V., Maganaris, C. N., & Loram, I. D. (2013). Human standing: Does the control strategy preprogram a rigid knee?. *Journal of applied physiology (Bethesda, Md.: 1985)*, 114(12), 1717–1729.
<https://doi.org/10.1152/JAPPLPHYSIOL.01299.2012>
- Donker, S. F., Roerdink, M., Greven, A. J., & Beek, P. J. (2007). Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. *Experimental brain research*, 181(1), 1–11.
<https://doi.org/10.1007/s00221-007-0905-4>
- Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, 39(2), 175–191.
<https://doi.org/10.3758/BF03193146>
- Fino, P. C., Peterka, R. J., Hullar, T. E., Murchison, C., Horak, F. B., Chesnutt, J. C., & King, L. A. (2017). Assessment and rehabilitation of central sensory impairments for balance in mTBI using auditory biofeedback: a randomized clinical trial. *BMC neurology*, 17(1), 41. <https://doi.org/10.1186/s12883-017-0812-7>
- Fischer, O. M., Missen, K. J., Tokuno, C. D., Carpenter, M. G., & Adkin, A. L. (2023). Postural threat increases sample entropy of postural control. *Frontiers in neurology*, 14, 1179237. <https://doi.org/10.3389/fneur.2023.1179237>

- Friedrich, M., Grein, H. J., Wicher, C., Schuetze, J., Mueller, A., Lauenroth, A., Hottenrott, K., & Schwesig, R. (2008). Influence of pathologic and simulated visual dysfunctions on the postural system. *Experimental brain research*, 186(2), 305–314. <https://doi.org/10.1007/s00221-007-1233-4>
- Gillespie, L. D., Robertson, M. C., Gillespie, W. J., Sherrington, C., Gates, S., Clemson, L. M., & Lamb, S. E. (2012). Interventions for preventing falls in older people living in the community. *The Cochrane database of systematic reviews*, 2012(9), CD007146. <https://doi.org/10.1002/14651858.CD007146.pub3>
- Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A., & Swinnen, S. P. (2009). Proprioceptive sensibility in the elderly: degeneration, functional consequences and plastic-adaptive processes. *Neuroscience and biobehavioral reviews*, 33(3), 271–278. <https://doi.org/10.1016/j.neubiorev.2008.08.012>
- Haid, T. H., Doix, A. M., Nigg, B. M., & Federolf, P. A. (2018). Age Effects in Postural Control Analyzed via a Principal Component Analysis of Kinematic Data and Interpreted in Relation to Predictions of the Optimal Feedback Control Theory. *Frontiers in aging neuroscience*, 10, 22. <https://doi.org/10.3389/fnagi.2018.00022>
- Haid, T. H., Zago, M., Promsri, A., Doix, A. M., & Federolf, P. A. (2019). PManalyzer: A Software Facilitating the Study of Sensorimotor Control of Whole-Body Movements. *Frontiers in neuroinformatics*, 13, 24.

<https://doi.org/10.3389/fninf.2019.00024>

- Haid, T., & Federolf, P. (2018). Human Postural Control: Assessment of Two Alternative Interpretations of Center of Pressure Sample Entropy through a Principal Component Factorization of Whole-Body Kinematics. *Entropy (Basel, Switzerland)*, 20(1), 30. <https://doi.org/10.3390/e20010030>
- Hasegawa, N., Tanaka, S., Mani, H., Inoue, T., Wang, Y., Watanabe, K., & Asaka, T. (2021). Adaptation of the compensatory stepping response following predictable and unpredictable perturbation training. *Frontiers in human neuroscience*, 15, 674960. <https://doi.org/10.3389/fnhum.2021.674960>
- Hayashi Y. (2007). Nihon Ronen Igakkai zasshi. *Japanese journal of geriatrics*, 44(5), 591–594. <https://doi.org/10.3143/geriatrics.44.591>
- Hilliard, M. J., Martinez, K. M., Janssen, I., Edwards, B., Mille, M. L., Zhang, Y., & Rogers, M. W. (2008). Lateral balance factors predict future falls in community-living older adults. *Archives of physical medicine and rehabilitation*, 89(9), 1708–1713. <https://doi.org/10.1016/j.apmr.2008.01.023>
- Hof, A. L., & Duysens, J. (2013). Responses of human hip abductor muscles to lateral balance perturbations during walking. *Experimental brain research*, 230(3), 301–310. <https://doi.org/10.1007/s00221-013-3655-5>
- Hof, A. L., Gazendam, M. G., & Sinke, W. E. (2005). The condition for dynamic stability. *Journal of biomechanics*, 38(1), 1–8.

<https://doi.org/10.1016/J.JBIOMECH.2004.03.025>

Holmes, M. L., Manor, B., Hsieh, W. H., Hu, K., Lipsitz, L. A., & Li, L. (2016). Tai Chi training reduced coupling between respiration and postural control.

Neuroscience letters, 610, 60–65. <https://doi.org/10.1016/j.neulet.2015.10.053>

Horak F. B. (1987). Clinical measurement of postural control in adults. *Physical therapy*, 67(12), 1881–1885. <https://doi.org/10.1093/ptj/67.12.1881>

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

Horak, F. B., & Macpherson, J. M., (1996), Postural Orientation and Equilibrium. In L. B. Rowell, & J. T. Sheperd (Eds.), *Handbook of Physiology, Section 12. Exercise: Regulation and Integration of Multiple Systems* (pp. 255-292). New York: Oxford University Press.

Horak, F. B., & Nashner, L. M. (1986). Central programming of postural movements: adaptation to altered support-surface configurations. *Journal of neurophysiology*, 55(6), 1369–1381. <https://doi.org/10.1152/jn.1986.55.6.1369>

Houglum, P. A., & Bertoti, D. B. (2011). Brunnstrom's clinical kinesiology. FA Davis.

Hu, Y., Guo, RQ., Min, S. H., Hui, M. S., Li, B. (2021), Disease burden on falls among older adults in China, 1990-2019. *Modern Preventive Medicine*, 48(9): 1542-1545, 1630.

<https://d.wanfangdata.com.cn/periodical/ChlQZXJpb2RpY2FsQ0hJTmV3UzIwMjIwMzIyEg94ZHlmeXgyMDIxMDkwMDIaCDQ3ZTJncWd4>.

Huxhold, O., Li, S. C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain research bulletin*, 69(3), 294–305.

<https://doi.org/10.1016/j.brainresbull.2006.01.002>

Iodice, P., Scuderi, N., Saggini, R., & Pezzulo, G. (2015). Multiple timescales of body schema reorganization due to plastic surgery. *Human movement science*, 42, 54–70. <https://doi.org/10.1016/j.humov.2015.04.009>

Iqbal, K., & Pai, Y. (2000). Predicted region of stability for balance recovery: motion at the knee joint can improve termination of forward movement. *Journal of biomechanics*, 33(12), 1619–1627. [https://doi.org/10.1016/s0021-9290\(00\)00129-9](https://doi.org/10.1016/s0021-9290(00)00129-9)

Ishida, T., Yamanaka, M., Takeda, N., & Aoki, Y. (2014). Knee rotation associated with dynamic knee valgus and toe direction. *The Knee*, 21(2), 563–566. <https://doi.org/10.1016/J.KNEE.2012.12.002>

Jebelli, H., Ahn, C. R., & Stentz, T. L. (2016). Fall risk analysis of construction workers using inertial measurement units: Validating the usefulness of the postural stability metrics in construction. *Safety science*, 84, 161–170. <https://doi.org/10.1016/J.SSCI.2015.12.012>

- Jiang, L., Kasahara, S., Ishida, T., Koshino, Y., Chiba, A., Yoshimi, K., Wei, Y., Samukawa, M., & Tohyama, H. (2023). Change in sensory integration and regularity of postural sway with the suspensory strategy during static standing balance. *Frontiers in Neurology*, 14, 1290986.
<https://doi.org/10.3389/fneur.2023.1290986>
- Jiang, L., Kasahara, S., Ishida, T., Wei, Y., Chiba, A., Samukawa, M., & Tohyama, H. (2023). Dual-task interference slows down proprioception. *Motor control*, 27(3), 465–479. <https://doi.org/10.1123/MC.2022-0075>
- Kal, E. C., Young, W. R., & Ellmers, T. J. (2022). Balance capacity influences the effects of conscious movement processing on postural control in older adults. *Human movement science*, 82, 102933.
<https://doi.org/10.1016/j.humov.2022.102933>
- Kapteyn, T. S., & de Wit, G. (1972). Posturography as an auxiliary in vestibular investigation. *Acta oto-laryngologica*, 73(2), 104–111.
<https://doi.org/10.3109/00016487209138918>
- Kasahara, S., & Saito, H. (2021). Mechanisms of postural control in older adults based on surface electromyography data. *Human movement science*, 78, 102803.
<https://doi.org/10.1016/J.HUMOV.2021.102803>
- Kasahara, S., Saito, H., Anjiki, T., & Osanai, H. (2015). The effect of aging on vertical postural control during the forward and backward shift of the center of pressure.

- Gait & posture*, 42(4), 448–454. <https://doi.org/10.1016/j.gaitpost.2015.07.056>
- Kim, H. Y., Kim, K. J., Yang, D. S., Jeung, S. W., Choi, H. G., & Choy, W. S. (2015). Screw-home movement of the tibiofemoral joint during normal gait: Three-dimensional analysis. *Clinics in orthopedic surgery*, 7(3), 303–309. <https://doi.org/10.4055/cios.2015.7.3.303>
- Kim, Y., Youm, C., Son, M., Kim, J., & Lee, M. (2017). The effect of knee flexor and extensor fatigue on shock absorption during cutting movements after a jump landing. *The Knee*, 24(6), 1342–1349. <https://doi.org/10.1016/j.knee.2017.09.007>
- Küng, U. M., Horlings, C. G., Honegger, F., Kremer, H. P., Bloem, B. R., van De Warrenburg, B. P., & Allum, J. H. (2009). Postural instability in cerebellar ataxia: Correlations of knee, arm and trunk movements to center of mass velocity. *Neuroscience*, 159(1), 390–404. <https://doi.org/10.1016/J.NEUROSCIENCE.2008.11.050>
- Kędziorek, J., & Błażkiewicz, M. (2020). Nonlinear Measures to Evaluate Upright Postural Stability: A Systematic Review. *Entropy (Basel, Switzerland)*, 22(12), 1357. <https://doi.org/10.3390/e22121357>
- Lam, F. M., Liao, L. R., Kwok, T. C., & Pang, M. Y. (2016). The effect of vertical whole-body vibration on lower limb muscle activation in elderly adults: Influence of vibration frequency, amplitude and exercise. *Maturitas*, 88, 59–64.

<https://doi.org/10.1016/j.maturitas.2016.03.011>

Liang, Z., Clark, R., Bryant, A., Quek, J., & Pua, Y. H. (2014). Neck musculature fatigue affects specific frequency bands of postural dynamics during quiet standing. *Gait & posture*, 39(1), 397–403.

<https://doi.org/10.1016/j.gaitpost.2013.08.007>

Lin, I. S., Lai, D. M., Ding, J. J., Chien, A., Cheng, C. H., Wang, S. F., Wang, J. L., Kuo, C. L., & Hsu, W. L. (2019). Reweighting of the sensory inputs for postural control in patients with cervical spondylotic myelopathy after surgery. *Journal of neuroengineering and rehabilitation*, 16(1), 96. <https://doi.org/10.1186/s12984-019-0564-2>

Loram, I. D., & Lakie, M. (2002). Direct measurement of human ankle stiffness during quiet standing: The intrinsic mechanical stiffness is insufficient for stability. *The journal of physiology*, 545(3), 1041–1053.

<https://doi.org/10.1113/JPHYSIOL.2002.025049>

Ma, C. Z., & Lee, W. C. (2017) A wearable vibrotactile biofeedback system improves balance control of healthy young adults following perturbations from quiet stance. *Human movement science*, 55, 54–60.

<https://doi.org/10.1016/J.HUMOV.2017.07.006>

Maki, B. E., & McIlroy, W. E. (2006). Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. *Age and*

ageing, 35 Suppl 2, ii12–ii18. <https://doi.org/10.1093/ageing/afl078>

Masouros, S. D., Bull, A. M. J., & Amis, A. A. (2010). (i) Biomechanics of the knee joint. *Orthopaedics and trauma*, 24(2), 84–91.

<https://doi.org/10.1016/j.mporth.2010.03.005>

Mauritz, K. H., & Dietz, V. (1980). Characteristics of postural instability induced by ischemic blocking of leg afferents. *Experimental brain research*, 38(1), 117–119.

<https://doi.org/10.1007/BF00237939>

Montero-Odasso, M. M., Kamkar, N., Pieruccini-Faria, F., Osman, A., Sarquis-Adamson, Y., Close, J., Hogan, D. B., Hunter, S. W., Kenny, R. A., Lipsitz, L. A., Lord, S. R., Madden, K. M., Petrovic, M., Ryg, J., Speechley, M., Sultana, M., Tan, M. P., van der Velde, N., Verghese, J., Masud, T., ... Task Force on Global Guidelines for Falls in Older Adults (2021). Evaluation of Clinical Practice Guidelines on Fall Prevention and Management for Older Adults: A Systematic Review. *JAMA network open*, 4(12), e2138911.

<https://doi.org/10.1001/jamanetworkopen.2021.38911>

Montesinos, L., Castaldo, R., & Pecchia, L. (2018). On the use of approximate entropy and sample entropy with centre of pressure time-series. *Journal of neuroengineering and rehabilitation*, 15(1), 116. [https://doi.org/10.1186/s12984-](https://doi.org/10.1186/s12984-018-0465-9)

[018-0465-9](https://doi.org/10.1186/s12984-018-0465-9)

Nakamura, R., Saito, H., and Nagasaki, H. (2016), Fundamental kinesiology, Ishiyaku

Publishers, Inc. sixth edition (2016) (in Japanese).

Nashner, L. M. & McCollum, G. (1985). The organization of human postural movements: A formal basis and experimental synthesis. *Behavioral and brain sciences*, 8(1), 135–150. <https://doi.org/10.1017/S0140525X00020008>

Oddsson, L. I., Wall, C., McPartland, M. D., Krebs, D. E., & Tucker, C. A. (2004). Recovery from perturbations during paced walking. *Gait & posture*, 19(1), 24–34. [https://doi.org/10.1016/s0966-6362\(03\)00008-0](https://doi.org/10.1016/s0966-6362(03)00008-0)

Oude Nijhuis, L. B., Bloem, B. R., Carpenter, M. G., & Allum, J. H. (2007). Incorporating voluntary knee flexion into nonanticipatory balance corrections. *Journal of neurophysiology*, 98(5), 3047–3059. <https://doi.org/10.1152/jn.01303.2006>

Pai, Y. C., & Patton, J. (1997). Center of mass velocity-position predictions for balance control. *Journal of biomechanics*, 30(4), 347–354. [https://doi.org/10.1016/S0021-9290\(96\)00165-0](https://doi.org/10.1016/S0021-9290(96)00165-0)

Peterka R. J. (2018). Sensory integration for human balance control. *Handbook of clinical neurology*, 159, 27–42. <https://doi.org/10.1016/B978-0-444-63916-5.00002-1>

Pollock, A. S., Durward, B. R., Rowe, P. J., & Paul, J. P. (2000). What is balance?. *Clinical rehabilitation*, 14(4), 402–406. <https://doi.org/10.1191/0269215500cr342oa>

Quek, J., Brauer, S. G., Clark, R., & Treleaven, J. (2014). New insights into neck-pain-related postural control using measures of signal frequency and complexity in older adults. *Gait & posture*, 39(4), 1069–1073.

<https://doi.org/10.1016/j.gaitpost.2014.01.009>

Ramdani, S., Seigle, B., Lagarde, J., Bouchara, F., & Bernard, P. L. (2009). On the use of sample entropy to analyze human postural sway data. *Medical engineering & physics*, 31(8), 1023–1031. <https://doi.org/10.1016/j.medengphy.2009.06.004>

Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human movement science*, 7(2-4), 265-300. [https://doi: 10.1016/0167-9457\(88\)90014-0](https://doi.org/10.1016/0167-9457(88)90014-0)

Richman, J. S., & Moorman, J. R. (2000). Physiological time-series analysis using approximate entropy and sample entropy. *American journal of physiology. Heart and circulatory physiology*, 278(6), H2039–H2049.

<https://doi.org/10.1152/ajpheart.2000.278.6.H2039>

Robinovitch, S. N., Feldman, F., Yang, Y., Schonnop, R., Leung, P. M., Sarraf, T., Sims-Gould, J., & Loughin, M. (2013). Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study. *Lancet (London, England)*, 381(9860), 47–54. [https://doi.org/10.1016/S0140-6736\(12\)61263-X](https://doi.org/10.1016/S0140-6736(12)61263-X)

Rogers, M. W., Creath, R. A., Gray, V., Abarro, J., McCombe Waller, S., Beamer, B. A.,

- & Sorkin, J. D. (2021). Comparison of lateral perturbation-induced step training and hip muscle strengthening exercise on balance and falls in community-dwelling older adults: A blinded randomized controlled trial. *The journals of gerontology. Series A, Biological sciences and medical sciences*, 76(9), e194–e202. <https://doi.org/10.1093/gerona/glab017>
- Rosker, J., Markovic, G., & Sarabon, N. (2011). Effects of vertical center of mass redistribution on body sway parameters during quiet standing. *Gait & posture*, 33(3), 452–456. <https://doi.org/10.1016/j.gaitpost.2010.12.023>
- Runge, C. F., Shupert, C. L., Horak, F. B., & Zajac, F. E. (1999). Ankle and hip postural strategies defined by joint torques. *Gait & posture*, 10(2), 161–170. [https://doi.org/10.1016/s0966-6362\(99\)00032-6](https://doi.org/10.1016/s0966-6362(99)00032-6)
- Santos, M. J., Kanekar, N., & Aruin, A. S. (2010). The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. *Journal of electromyography and kinesiology: official journal of the International Society of Electrophysiological Kinesiology*, 20(3), 398–405. <https://doi.org/10.1016/j.jelekin.2010.01.002>
- Shumway-Cook, A., & Woollacott, M. H. (1995). Theory and practical applications. *Motor control*, 89-90.
- Sienko, K. H., Balkwill, M. D., & Wall, C., 3rd (2012). Biofeedback improves postural control recovery from multi-axis discrete perturbations. *Journal of*

neuroengineering and rehabilitation, 9, 53. [https://doi.org/10.1186/1743-0003-9-](https://doi.org/10.1186/1743-0003-9-53)

[53](#)

- Siragy, T., & Nantel, J. (2018). Quantifying dynamic balance in young, elderly and Parkinson's individuals: A systematic review. *Frontiers in aging neuroscience*, 10, 387. <https://doi.org/10.3389/fnagi.2018.00387>
- Siragy, T., Russo, Y., Young, W., & Lamb, S. E. (2023). Comparison of over-ground and treadmill perturbations for simulation of real-world slips and trips: A systematic review. *Gait & posture*, 100, 201–209. <https://doi.org/10.1016/j.gaitpost.2022.12.015>
- Sugama, A., Tonoike, Y., & Seo, A. (2020). Investigation of the functional stability limits while squatting. *Human factors & ergonomics in manufacturing & service industries*, 30(3), 195–203. <https://doi.org/10.1002/HFM.20833>
- Swinton, P. A., Lloyd, R., Keogh, J. W., Agouris, I., & Stewart, A. D. (2012). A biomechanical comparison of the traditional squat, powerlifting squat, and box squat. *Journal of strength and conditioning research*, 26(7), 1805–1816. <https://doi.org/10.1519/JSC.0b013e3182577067>
- Taniguchi, S., Ishida, T., Yamanaka, M., Ueno, R., Ikuta, R., Chijimatsu, M., Samukawa, M., Koshino, Y., Kasahara, S., & Tohyama, H. (2022). Sex difference in frontal plane hip moment in response to lateral trunk obliquity during single-leg landing. *BMC sports science, medicine & rehabilitation*, 14(1),

70. <https://doi.org/10.1186/s13102-022-00460-y>

Tinetti M. E. (2003). Clinical practice. Preventing falls in elderly persons. *The New England journal of medicine*, 348(1), 42–49.

<https://doi.org/10.1056/NEJMcp020719>

Tinetti, M. E., Baker, D. I., Garrett, P. A., Gottschalk, M., Koch, M. L., & Horwitz, R. I. (1993). Yale FICSIT: risk factor abatement strategy for fall prevention. *Journal of the American Geriatrics Society*, 41(3), 315–320.

<https://doi.org/10.1111/j.1532-5415.1993.tb06710.x>

Todorov E. (2004). Optimality principles in sensorimotor control. *Nature neuroscience*, 7(9), 907–915. <https://doi.org/10.1038/nm1309>

Todorov, E., & Jordan, M. I. (2002). Optimal feedback control as a theory of motor coordination. *Nature neuroscience*, 5(11), 1226–1235.

<https://doi.org/10.1038/nm963>

Troy, K. L., Donovan, S. J., Marone, J. R., Bareither, M. L., & Grabiner, M. D. (2008).

Modifiable performance domain risk-factors associated with slip-related falls.

Gait & posture, 28(3), 461–465. <https://doi.org/10.1016/j.gaitpost.2008.02.008>

Ueno, R., Navacchia, A., DiCesare, C. A., Ford, K. R., Myer, G. D., Ishida, T.,

Tohyama, H., & Hewett, T. E. (2020). Knee abduction moment is predicted by lower gluteus medius force and larger vertical and lateral ground reaction forces during drop vertical jump in female athletes. *Journal of biomechanics*, 103,

109669. <https://doi.org/10.1016/j.jbiomech.2020.109669>

Wachholz, F., Kockum, T., Haid, T., & Federolf, P. (2019). Changed Temporal Structure of Neuromuscular Control, Rather Than Changed Intersegment Coordination, Explains Altered Stabilographic Regularity after a Moderate Perturbation of the Postural Control System. *Entropy (Basel, Switzerland)*, 21(6), 614.

<https://doi.org/10.3390/e21060614>

Wachholz, F., Tiribello, F., Promsri, A., & Federolf, P. (2019). Should the Minimal Intervention Principle Be Considered When Investigating Dual-Tasking Effects on Postural Control?. *Brain sciences*, 10(1), 1.

<https://doi.org/10.3390/brainsci10010001>

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait and posture*, 3, 193-214. [http://dx.doi.org/10.1016/0966-6362\(96\)82849-9](http://dx.doi.org/10.1016/0966-6362(96)82849-9)

Winter, D. A., Prince, F., Frank, J. S., Powell, C., & Zabjek, K. F. (1996). Unified theory regarding A/P and M/L balance in quiet stance. *Journal of neurophysiology*, 75(6), 2334–2343. <https://doi.org/10.1152/jn.1996.75.6.2334>

Wretenberg, P., Ramsey, D. K., & Németh, G. (2002). Tibiofemoral contact points relative to flexion angle measured with MRI. *Clinical biomechanics (Bristol, Avon)*, 17(6), 477–485. [https://doi.org/10.1016/s0268-0033\(02\)00036-0](https://doi.org/10.1016/s0268-0033(02)00036-0)

Yentes, J. M., & Raffalt, P. C. (2021). Entropy Analysis in Gait Research: Methodological Considerations and Recommendations. *Annals of biomedical*

engineering, 49(3), 979–990. <https://doi.org/10.1007/s10439-020-02616-8>

Zhu, R. T., Lyu, P. Z., Li, S., Tong, C. Y., Ling, Y. T., & Ma, C. Z. (2022). How does lower limb respond to unexpected balance perturbations? New insights from synchronized human kinetics, kinematics, muscle electromyography (EMG) and mechanomyography (MMG) data. *Biosensors*, 12(6), 430.

<https://doi.org/10.3390/bios12060430>

de Groot, M. H., van der Jagt-Willems, H. C., van Campen, J. P., Lems, W. F., Beijnen, J. H., & Lamothe, C. J. (2014). A flexed posture in elderly patients is associated with impairments in postural control during walking. *Gait & posture*, 39(2), 767–772. <https://doi.org/10.1016/j.gaitpost.2013.10.015>

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of biomechanics*, 29(9), 1223–1230.
[https://doi.org/10.1016/0021-9290\(95\)00178-6](https://doi.org/10.1016/0021-9290(95)00178-6)

Author's publications and conference presentations

Select List of Relevant Works

Publications

- **Linjing Jiang**, Satoshi Kasahara, Tomoya Ishida, Yuta Koshino, Ami Chiba, Yuting Wei, Mina Samukawa, Harukazu Tohyama. Effect of suspensory strategy on balance recovery after lateral perturbation. Human Movement Science. vol. 94 1031842024. 2024.04, IF: 2.1
- **Linjing Jiang**, Satoshi Kasahara, Tomoya Ishida, Yuta Koshino, Ami Chiba, Kazumasa Yoshimi, Yuting Wei, Mina Samukawa, Harukazu Tohyama. Change in sensory integration and regularity of postural sway with the suspensory strategy during static standing balance. Front. Neurol. vol.14 1290. 2023.08, IF: 3.4
- Satoshi Kasahara, Tomoya Ishida, **Linjing Jiang**, Ami Chiba, Mina Samukawa, Harukazu Tohyama. Relationship between the COM Motion and Lower Extremity and Trunk during the Squat. Journal of Human Kinetics.2023, (in press). IF: 2.3

Presentations

- **Linjing Jiang**, Satoshi Kasahara, Tomoya Ishida, Yuta Koshino, Mina Samukawa, Harukazu Tohyama. The Effect of Suspensory Strategy on Postural Control under Lateral Perturbations: A Study on COM Height and Balance Performance. XXIX Congress of International/Japanese Society of Biomechanics. Fukuoka, Japan,

2023.08

- ・ **江林京**、笠原敏史、石田知也、越野裕太、吉見和政、千葉愛未、寒川美奈、遠山晴一、「スクワット姿勢時の膝関節屈曲角度の違いによる重心動揺の規則性と感覚入力への影響」, 第 50 回日本臨床バイオメカニクス学会, 兵庫県姫路市,

2023.11

Lists of other works

Publications

- ・ **Linjing Jiang**, Satoshi Kasahara, Tomoya Ishida, Yuta Koshino, Yuting Wei, Ami Chiba, Mina Samukawa, Harukazu Tohyama. Dual-Task Interference Slows Down Proprioception. Motor control, vol. 27(3), 465–479, 2023. 01, IF: 1.5
- ・ **Linjing Jiang**, Satoshi Kasahara, Tomoya Ishida, Liejun Shen, Zhisheng Xu, Dijin Jiang, Yu ting Wei, Mina Samukawa, Harukazu Tohyama. Rehabilitation Effects after Knee Arthroplasty in a core hospital in the local area in China. Journal of Asian Rehabilitation Science, vol. 3(3) pp. 40-46, 2020. 05
- ・ 和田 千尋、笠原 敏史、阿部 はるか、平野 美千代、萬井 太規、石田 知也、**江林京**、「北海道の全市における特定保健指導の運動指導の現状と今後の課題」, 人間ドック, 第 34 巻 4 号, pp. 581-589, 2019. 12

Presentations

- ・ **Linjing Jiang**, Satoshi Kasahara, Tomoya Ishida, Liejun Shen, Zhisheng Xu, Dijin

Jiang, Yuting Wei, Mina Samukawa, Harukazu Tohyama, The status of the rehabilitation for the total knee replacement in China. The 4th FHS International Conference, Sapporo (Japan), 2019.07

- ・ **Linjing Jiang**, Satoshi Kasahara, Wei Yuting, Kentaro Watanabe, Tomoya Ishida, Mina Samukawa, Harukazu Tohyama, The effects of muscle training with a random order for ankle plantarflexors in no-trained healthy young adults. JOSKAS-JOSSM2022, Sapporo (Japan), 2022.06
- ・ **江林京**、笠原敏史、衛雨亭、石田知也、寒川美奈、遠山晴一、「膝関節覚の定量的評価方法の検討」, 第 23 回日本体力医学会北海道地方会学術集会, オンライン開催 (札幌市), 2021. 04
- ・ **江林京**、笠原敏史、衛雨亭、千葉愛未、石田知也、寒川美奈、遠山 晴一、「認知課題が膝関節の運動覚・位置覚の応答に及ぼす影響」, 第 76 回日本体力医学会大会, オンライン開催(三重県), 2021. 09
- ・ 和田千尋、笠原敏史、阿部はるか、平野美千代、**江林京**、「特定保健指導の運動指導の課題と理学療法への期待」, 第 6 回日本予防理学療法学会学術大会, 広島市, 2019. 10
- ・ 千葉愛未、笠原敏史、**江林京**、衛雨亭、石田知也、寒川美奈、遠山晴一、「身体能力認識誤差と運動習慣の関係」, 第 23 回日本体力医学会北海道地方会学術集会, オンライン開催 (札幌市), 2021. 04
- ・ 千葉愛未、笠原敏史、**江林京**、衛雨亭、石田知也、寒川美奈、遠山晴一、「若年者

の運動習慣と身体認識誤差についての検討」, 第 46 回日本運動療法学会学術集会,
オンライン開催 (札幌市), 2021. 06

- ・ 和田千尋、笠原敏史、阿部はるか、平野美千代、石田知也、江林京, 「北海道における特定保健指導の運動指導の現場と理学療法士への期待」, 第 40 回日本臨床運動療法学会学術集会, 京都市, 2021. 09
- ・ 笠原敏史、衛雨亭、江林京、千葉愛未、石田知也、寒川美奈、遠山晴一, 「筋力調整能力へのランダム練習の有効性について」, 第 27 回日本基礎理学療法学会学術大会, 大阪市, 2022. 10
- ・ 千葉愛未、笠原敏史、江林京、石田知也、寒川美奈、遠山晴一, 「身体活動量が身体認識誤差へ与える影響」, 第 9 回日本予防理学療法学会学術大会, 東京都, 2022. 11
- ・ 吉見和政、江林京、笠原敏史、石田知也、越野裕太、寒川美奈、遠山晴一, 「股関節屈筋群へのスタティックストレッチングが動的バランスに与える効果の検討」, 第 25 回日本体力医学会北海道地方会大会, 札幌市, 2023. 04

Acknowledgements

I would like to express my heartfelt gratitude to my supervisor, Professor. M.D., Ph.D. Harukazu Tohyama, as well as my associate supervisor, Assistant Professor. Ph.D. Satoshi Kasahara, who have given me the great opportunity to pursue my dreams and the chance to explore the field of postural control in greater depth. Dr. Tohyama and Dr. Kasahara have been very supportive throughout my doctoral studies, always standing up for me when I was stubborn and inspiring new ideas that led to the completion of this dissertation. Their thoughtful guidance and invaluable comments provided me with the direction and freedom to develop new skills in line with my interests. I would also like to express my gratitude to the supervisors of the Musculoskeletal Research Laboratory: Mina Samukawa, Tomoya Ishida, and Yuta Koshino, who have guided my research for the past three years, provided technical support, and offered advice on fine-tuning the direction of the research when it was stagnating. Thanks to their valuable discussions and fun times during research hours, my doctoral studies has been a perfect combination of hard work and relaxed atmosphere. I would be glad to express my profound gratitude to the members of the dissertation committee: Associate Professor Mina Samukawa as the chief examiner, Professor Mukaino Masahiko, and Professor Harukazu Tohyama as the sub-chief examiners. Their commitment to reviewing this doctoral thesis was greatly appreciated. Their insightful revisions significantly enhanced the quality of this thesis. Their insightful revisions significantly enhanced the quality of this thesis. Special thanks

to Ami Chiba, Shenlei Tang, Kazumasa Yoshimi, and Yi Zeng, who provided free help when I was short of manpower for my work, and helped me with the details of the algorithms and writing related to my research.

I would also like to thank all my friends who stuck with me even when I had to prioritize my research over attending cozy parties. I would also like to thank my parents, Yunfen Chen, Youcai Jiang, my mother's husband, Chen Guohong, for selflessly guiding my life and supporting me in my spare time and studies. Last but not least, I would like to thank my girlfriend, Zan Wang, who has always been there for me, sharing my research frustrations and listening to my complaints.