A biomechanist's guide to defying gravity: An exploration of the physiological link between sensorineural function and postural control

By

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Abstract

In the United States, 28.7% of adults aged 65 or older experience a fall every year, amounting to an estimated 29 million falls.[1] Of these falls, 7 million result in injuries that require medical treatment and contribute to an estimated $50 billion in medical costs.[1,2] Even when provided proper medical care, fallers experience lasting mobility problems and face an increased risk of future falls, creating a vicious feedback loop of falls and injury. Though seemingly mundane, maintaining balance is a precarious act, requiring the body to overcome one of the most ubiqiutous forces in the universe – gravity. To do so, the body must constantly monitor conditions, both internal and external, and initiate fine muscular contractions to remain upright. One of the primary contributors to falls in older adults is visual, vestibular, and somatosensory degeneration, which dampens sensory input and limits an individual's ability to produce well-informed, coordinated movements and overcome physical obstacles.[3–5] Because these changes can initially be very subtle, predicting the first fall, and therefore preventing the vicious fall-injury cycle, can be incredibly challenging. Thus, the need for more sensitive measures of balance is apparent. The present work aims to tackle this gap in measurement through the evaluation of physiologically-inspired measures of sway and their relation to changes in sensation ability. More specifically, this work will capture the individual contributions and integration of vision, vestibular sense, and somatosensation as well as evaluate potential opportunities to augment sensation through the use of vibratory stochastic facilitation. This dissertation contains three specific aims, (1) characterizing sway behavior during a simulated, progressive decline in somatosensory function, (2) quantifying the influence of vision, vestibular sense, and somatosensation on underlying postural control mechanisms, and (3) investigating the effect of subthreshold vibratory noise on postural sway. In all of these aims, analysis will employ rambling-trembling decomposition of the center-of-pressure, a method that

seeks to understand motion from mechanistic perspective by separating sway into rambling (central, supraspinal) and trembling (peripheral, spinal) components. Across these three studies, it is apparent that spinal control mechanisms, as opposed to supraspinal, are influenced most significantly by sensorineural input (or lack thereof). In healthy individuals facing sensory challenges, such as those included in this work, this is indicative of an intact ability to set and reset an equilibrium point, but an impaired ability to enact this "plan," creating a large discrepancy between planned and actual motion. Though more work is required to fully understand this effect, the present work serves as a foundation for future investigations that will include a wider variety of sensory challenges and clinical populations. With this knowledge, we may one day be able to enhance fall risk assessment techniques and rehabilitation practices using a more efficient, targeted approach. Ultimately, these advancements may reduce the prevalence of geriatric falls and improve overall quality of life with age.

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If I've learned anything over the past four and a half years, I've learned that engineering, graduate school, and life in general is a team sport. I'm happy to report that my last two remaining brain cells have joined forces with so many of the brilliant minds that I am surrounded with on a daily basis. There are so many people that have helped shape who I am today and I cannot begin to thank you all enough for the role you have played in my life, inside and outside the lab.

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List of Abbreviations

ANOVA	Analysis of variance
AP	Anteroposterior (front-back)
BL	Baseline trial
CNS	Central nervous system
COP	Center-of-pressure
EC	Eyes closed
EO	Eyes open
F0	0” of foam
F1	1/8” of foam
F2	1/4" of foam
F3	1/2" of foam
F4	1” of foam
ML	Mediolateral (side-side)
PNS	Peripheral nervous system
RM	Rambling time series
RMS	Root-mean-square
SampEn	Sample entropy
STIM	Stimulation trial
TR	Trembling time series

Chapter 1: Introduction

Background & Motivation

Accidental falls are the number one cause of injury-related death in adults aged 65 and older.[1] Of those that survive these falls, an estimated 7 million result in injuries that require medical attention, amounting to over $50 billion in medical expenses every year.[1–3] Even after enduring intensive medical treatments and rehabilitation, fallers often face lasting detrimental effects to their balance and mobility, limiting activity and increasing the likelihood of future falls.[4] In fact, in a study of 325 older adults, 57% of subjects that had a fall in the previous year experienced at least one new fall, 31% suffered two or more additional falls, and 19% survived 3 or more falls over the course of the next twelve months.[4]

Though often taken for granted, postural control is actually quite complex. In everyday activities such as walking, running, or even standing, the sensorimotor system is continuously fighting the gravitational pull of the Earth in order to remain stable. To do so, the body must constantly collect visual, vestibular, and somatosensory (touch) information. Using all of this input, the body is able to fine-tune muscle activation such that it may remain upright, a position that is, biomechanically, very difficult.

The cause of a fall is often multifactorial, but can be linked to degeneration of one or more of these sensory systems. In aging, these senses degrade, increasing the threshold magnitude required for sensation, therefore decreasing the likelihood of perceiving environmental and proprioceptive stimuli.[5,6] Without such input, the body cannot accurately assess its position in space or make appropriate corrections, ultimately decreasing stability and increasing the risk of falls. *Although sensation is vital to stability, the influence of vision, vestibular sense, and somatosensation on postural control remains poorly understood*. Achieving a more complete

understanding of the role of sensation in balance would contribute significantly to our ability to identify early signs of fall risk and inform clinical risk mitigation strategies.

A novel center-of-pressure (COP) analysis technique, called rambling-trembling decomposition, seeks to expand our understanding of postural control and the role of the nervous system in modulating fluctuations.[7] COP has been studied extensively, but this new, widely unexplored rambling-trembling methodology unlocks a myriad of new information by decomposing the COP signal into rambling (RM) and trembling (TR) components that correspond to large scale movement of an equilibrium point and oscillation around this point, respectively. Preliminary RM-TR studies involving subjects with neurological disorders (i.e. Parkinson's, stroke, diabetic peripheral neuropathy) suggest that RM may be dictated by the central nervous system (CNS), while TR is controlled primarily by the peripheral nervous system (PNS).[8–12] However, there remains a substantial gap in knowledge regarding the effects of sensory input on these RM-TR measures.

In this study, we will explore the effects of visual, vestibular, and somatosensory input on postural sway through the examination of RM-TR components of center of pressure (COP). We will expand our understanding of postural control with regard to sensory input, utilizing rambling-trembling methodologies that are capable of isolating the underlying mechanisms of sway. *Ultimately, this work could be used to link sway patterns with the sensorineural conditions that influence them, improving our ability to identify and treat early symptoms of fall risk.*

Specific Aims

There are three specific aims included in this dissertation, each one seeking to capture different contributors to balance. Analytical methodologies are largely mirrored between aims, all utilizing

postural control-inspired analysis techniques (rambling-trembling decomposition), allowing us to elucidate the underlying physiological mechanisms that dictate sway with respect to magnitude, variability, and predictability. To achieve this overarching goal, the three specific aims are as follows:

Specific Aim 1: Simulated Somatosensory Deficit in Young Adults

It is often difficult to isolate the influence of an individual source of input in a complex, dynamical system (like human balance), and even more so to track its effects over a spectrum of magnitudes. However, the use of foam in this aim permits purposeful manipulation of the availability of somatosensory cues, allowing for the study of "deficit" progression. Although not a perfect model for true age-related somatosensory loss, foam dampens many pressure-based cues at the plantar surface that results in changes to sway that mimic many characteristics of aging. In this aim, our understanding of this effect is deepened using a range of foam thicknesses, allowing us to map this effect on an incremental basis. There are two hypotheses for this aim: (1.1.a), range, (1.1.b) variability and (1.1.c) predictability will increase across foam thickness for all measures, and (1.2) TR will demonstrate the lowest variability, magnitude, and predictability compared to COP and RM.

Specific Aim 2: Sensory Re-weighting between Visual, Vestibular, and Somatosensory Input

Sensory re-weighting is a well-known phenomenon in which the body redirects cognitive weight of an individual sense onto another; it is a common strategy in certain sensory challenges, such as standing with eyes closed, and in older adults, who experience declines in one or more senses that are vital to maintaining balance. This process has been studied extensively in the clinical setting using the Sensory Organization Test, a battery of six conditions that seek to isolate contributions of vision, somatosensation, and vestibular sense to postural sway. The hypotheses for this aim are

as follows: (2.1) as task difficulty (i.e. condition number) increases, (2.1.a) range, (2.1.b) variability, and (2.1.c) predictability will increase and (2.2) vision will demonstrate a significant individual contribution to sway.

Specific Aim 3: Impact of Stochastic Facilitation-assisted Somatosensation

Despite the prevalence of somatosensory loss, there are virtually no effective, reliable therapies to treat this problem. Stochastic facilitation-based therapy has the potential to offer a new, non-invasive but effective treatment for these individuals, but there remain questions regarding its efficacy, best practices, and underlying physiological mechanisms. In this study, healthy older adults will be exposed to subthreshold vibratory noise and stand quietly while sway data is collected. Doing this will allow for direct assessment of the influence of stochastic facilitation on balance by comparing baseline and during-stimulation postural sway. This aim has two hypotheses: (3.1) stochastic facilitation will produce (3.1.a) less predictable, (3.1.b) less variable, and (3.1.c) lesser magnitude sway in COP and its RM and TR components, as compared to the non-vibration control, and (3.2) the TR time series will show more prominent changes to predictability, variability, and magnitude during vibration than RM or COP.

Dissertation Content

This dissertation is composed of six chapters:

Chapter 1: An introduction of the overarching goal of this work and its three specific aims

Chapter 2: An in-depth discussion of relevant background information, including anatomy and physiology, balance mechanics, and research-based and clinical methods of sway assessment

Chapters 3-5: Manuscript-style presentation of each of the three specific aims

Chapter 6: A summary of key findings across all studies as well as a discussion of limitations and proposed future work

Chapter 2: Background

Unlike many animals, humans developed the ability to stand, walk, run, and play on a mere two legs. Although the intricacies of evolution and natural selection that ultimately resulted in upright stance are outside the scope of this work, the miracle of bipedal locomotion is certainly not.

As terrestrial beings, humans (and everything else on this planet) are constantly subjected to the force of gravity, an unwavering, incessant pull toward the Earth. Luckily, many forms of life on this planet have evolved with the ability to counteract this pull by exerting forces of our own, granting us the freedoms that accompany independent movement. Somewhere far, far down our ancestral line, humans took these freedoms to a new level, evolving from quadrupeds to bipeds. With this change came many additional adaptations to the body that allowed us to move safely and efficiently with only two limbs for support, but maintaining balance remains a precarious task.

Bipedal stance is inherently unstable; with only two legs, we must somehow exert the perfect amount of muscle force to not only oppose gravity but also to remain upright, a position that is biomechanically very intricate. From infancy to childhood, we learn (mostly through trial-and-error) to develop the right recipe of muscle contraction and relaxation that allows us to remain steady on two legs. Often taken for granted in adulthood, an act as simple as standing requires complex, systematic integration of sensory input and neurological control.

2.1 Balance Physiology

There are three essential pillars of human motion: sensation, cognitive processing, and action. Occurring nearly simultaneously, the body is constantly gathering data, planning its next move, contracting muscles, and relaying all of this information in a continuous feedback loop. When each component of this system is working properly, the body is capable of conquering miraculous feats – even (partially) defying gravity.

2.1.1 Sensation

The first of these pillars, sensation, is what allows us to gather information about ourselves and our environment. The body houses a complex circuit of neurons and specialized sensors that form the nervous system. The nervous system is divided into two subsystems, central and peripheral, that work in tandem to control all bodily processes and direct motion. The central nervous system is composed only of the brain and spinal cord and is responsible for a significant portion of everyday functionality, including thoughts, speech, reflexes, sensation, and motion. The peripheral nervous system is comprised of all of the nerves and sensors that extend out from the spinal cord, and serves as a communication network between the body and the central nervous system.

The fundamental building block of both the central and peripheral nervous systems is a simple neuron, or nerve cell. Neurons are responsible for relaying messages within the body using electrical signals. The neuron is composed of three primary structures, the dendrite, the axon, and the axon terminal. Dendrites receive signals from other neurons or sensors and, depending on the strength of the incoming signal, may trigger an electrical potential that relays this message along the axon. If triggered, neurotransmitters, such as dopamine, serotonin, or acetylcholine, are released from the axon terminals into the synaptic region between this neuron and the next, continuing the succession of neural impulses.

The “decision” to relay these messages is determined by the changes in electrical voltage within the dendrite. Neurons have a resting voltage of approximately -70mV. When a neuron is stimulated, this voltage is increased. If this change is large enough to exceed a threshold of -55mV, it initiates a rapid succession of membrane depolarizations within the neuron, called an action potential. Once passing this threshold, sodium channels are opened, causing an influx of sodium ions (Na+) and rapidly depolarizing the neuron. After the potential reaches a maximum of +40mV,

these sodium ion channels are closed and potassium ion (K+) channels open, causing an efflux of potassium that repolarizes the neuron and returns it to its resting state of -70mV.

The ability of the neuron to achieve threshold potential is dependent on the strength of the stimulus (or stimuli). This stimulus can be internal, initiated by conditions within the body, or external, caused by environmental conditions, but both internal and external stimuli as essential to sensation and therefore healthy balance. The body has specialized sensors to perceive a wide variety of stimuli, including taste, sound, touch, and smell, but the three primary sources of sensory input that are crucial to maintain balance include: somatosensation (touch), vestibular sense, and vision. Each individual sense provides unique insight into the body's position, both in space and relative to itself, and the speed by which it may or may not be moving.

Somatosensation

The origin of the term somatosensation is somewhat literal, derived from the latin root of "somato," meaning "body." Our bodies are composed mostly of skin and soft tissues that contain sensory receptors, including mechanoreceptors and proprioceptors, that are crucial to maintaining postural control.[5] Human skin contains four main types of mechanoreceptors: Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini corpuscles.[13] Mechanoreceptors are primarily responsible for sensing tactile stimuli, allowing for perception of pressure, texture, and vibration. In addition to these mechanoreceptors, we also have several proprioceptors, including muscle spindles, Golgi tendon organs, and joint receptors, that aid in our ability to assess our muscle and joint positions. Each type of receptor is specially attuned to different types of mechanical stimulation and can be described as either fast- or slow-adapting based on the speed by which they "adapt", or become desensitized, to an ongoing (static) stimulus. A summary of these characteristics can be found in Table 1.[14]

Table 1. Somatosensory receptors of the human body

	Receptor Type	Location	Adaptability	Function
Mechanoreceptor	Meissner's corpuscle	Glabrous (hairless) skin	Fast	Touch, dynamic pressure
	Pacinian corpuscle	Subcutaneous skin tissue	Fast	Deep pressure, vibration
	Merkel's disk	Skin, hair follicles	Slow	Touch, static pressure
	Ruffini corpuscle	Skin	Slow	Skin stretch
Proprioceptor	Muscle spindle	Muscles	Mixed	Muscle length
	Golgi tendon organ	Tendons	Slow	Muscle force (tension)
	Joint receptor	Joints	Fast	Joint position

Vestibular Sense

The vestibular sense is fine tuned to detect head position and rotations. It is composed of several structures, including the semicircular canals (lateral, superior, and posterior) and the otolith organs (the utricle and the saccule). These structures are located in the inner ear and serve distinct sensory functions. The semicircular canals consist of three interconnected loops of fluid-filled tubes. Similar to a gyroscope, each loop is oriented approximately 90 degrees from one another and detect rotational motion in three dimensions, often referred to as roll, pitch, and yaw (Figure 1).[15,16] The utricle and saccule are structured somewhat differently, with a simple fluid filled chamber with a small calcium carbonate crystal. The term "otolith" refers literally to this crystal, translating to "ear stone." The utricle and saccule are adapted to detect linear motion and

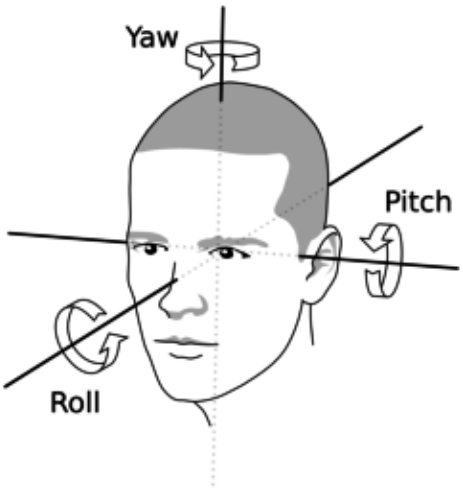

Figure 1. Roll, pitch, and yaw directions of the head

orientation, with the utricle primarily detecting horizontal acceleration and the saccule most sensitive to vertical acceleration.

Figure 2. Depiction of a typical vestibular hair cell

The entirety of the vestibular system is dependent on a base unit of sensation, the hair cell (Figure 2). These hair cells are located within each of the vestibular system's structures and detect fluid flow using a collection of protruding sensors, called the cilia (stereocilia and kinocilium). As fluid is shifted within its respective structure's enclosed chamber, as it does while tilting the head or leaning, the cilia deform in the direction of flow, triggering an action potential and subsequent sensation of orientation or movement stimuli. Even during an activity as simple as quiet standing, the vestibular system provides information that is vital to the maintenance of equilibrium.

Vision

Vision has long been known for its significance in the performance of activities of daily living, like walking, running, or climbing stairs, due to its ability to assess the environment and identify incoming obstacles. Similar to vestibular sense and somatosensation, vision relies on a smaller unit of sensation to gather information. For the visual system, the base unit of measurement is the photoreceptor. There are two types of photoreceptors, rods and cones, that are responsible for detecting light. Rods are active at low light conditions and aid in motion detection, while cones are capable of detecting color and add a higher level of acuity (fine detail) to an image.[17,18]

These photoreceptors are located in the retina, a layer of nerve tissue located in the back of the eye. As light enters the eye, the lens focuses the image on the retina, which then gathers this

information and converts it into a neural signal (using photoreceptors) for further processing by the nervous system. At the very center of the retina is the macula, a region with the highest density of photoreceptors, and of cones in particular. The macula is the primary source of central vision, which allows us to perform activities with a high level of focus, such as reading or driving. Rods are scattered throughout the retina and contribute significantly to peripheral vision, which aids in the detection of motion, both of external objects and of the visual field (that occurs when your body is moving). Of these two types of vision, the peripheral visual system is thought to serve as the primary contributor to postural control, aiding in a person's awareness of their position in space, or self-motion.[17,19] This is achieved by the peripheral visual system's specialized ability to assess lamellar optical flow produced by linear motion or rotations in the roll, pitch, and yaw directions of the head.[20]

When combined, somatosensation, vestibular sense, and vision provide a comprehensive view of the body's position and the manner in which it may or may not be moving. Although the senses are often studied as distinct entities, there is certainly a degree of interdependence required to maintain balance; just as the flavor of a food cannot be fully experienced without both the sense of taste and smell, balance is most efficient when sensory input from multiple sources is integrated.

2.1.2 Cognitive Processing

While the senses collect sensory information, providing the right signal input to maintain balance, postural control is only achieved when the brain can (a) construct this input into a cohesive, well-informed image of the body's position and (b) plan and initiate the body's actions and reactions to this position. Though the inner workings of the brain remain relatively enigmatic, there are two distinct regions known to contribute to sensory integration and motor planning: the motor cortex and the cerebellum.

The cerebrum composes the majority of brain tissue and is divided into various regions, or "cortices," that have been linked to specific functions, like speech, auditory processing, and memory. Located in the frontal lobe, the motor cortex is composed of three subregions, including the primary motor cortex, the premotor cortex, and the supplementary motor area. The exact functions of each of these structures remains heavily debated, but are hypothesized to include postural control during stance, neural signal generation for voluntary movement, and sensory signal integration.[21–23]

The cerebellum, often called the "little brain," is a structure of the hindbrain, located at the back of the head, that is responsible for a large majority of balance required for complex motor function, like walking and standing. It contributes significantly to both feedforward motor control, which allows for corrections to large perturbations to the center of mass, and sequencing, which integrates temporal and spatial information to form a cohesive perception of an event.[24,25]

Like in the countless other functions of the body, the brain acts as an incredibly complex computing system. It takes incoming information, processes it, determines the next steps with consideration of both the current state and the larger movement goal, and initiates this action plan by sending electrically-coded instructions to the body. Using these instructions, the muscles follow a detailed how-to guide for completing the action, including where, when, and how much to contract certain muscles.

2.1.3 Biomechanical Action

The key driving "force" in the body is the musculoskeletal system. Through the generation of both internal and external forces, muscles allow us to physically interact with the environment. Even a task as simple as sitting upright in a chair requires us to overcome the pull of gravitational force to remain stable.

Skeletal muscles of the body, such as the quadriceps, are composed of smaller sections of muscle tissue called fascicles, which break down further into muscle fibers, and then into individual muscle cells, or myofibrils. Each myofibril is composed of a series of individual contractile units, or sarcomeres. Within the sarcomere are two structures, actin and myosin, that interact to generate force. When stimulated, myosin undergoes a cascade of reactions that cause it to (1) attach to the actin, forming a crossbridge, (2) pivot, or perform a "power stroke," pulling the entire structure, and (3) detach from the actin and reset the system.[26] On a micro-scale, this results in the sliding of individual filaments of actin and myosin; on a macro-scale, this is a muscle contraction.

Muscles are often defined based on their strength and speed of contraction, which are determined by the number and orientation of myofibrils. Depending on the location in the body, frequency of use, and nature of the action(s), muscles will adapt to optimize efficiency. A canonical example of this is obvious when compare the physique of a runner versus a bodybuilder. Runners are focused mostly on speed, in which their myofibrils must contract as fast as possible; to accomplish this, myofibrils will often orient themselves in series (end to end), creating a leaner, longer build. Bodybuilders, on the other hand, are more concerned with maximizing the amount of force that they can overcome, relying heavily on myofibrils oriented in parallel (side to side).

Regardless of the specific pattern of myofibril alignment, nearly every skeletal muscle group of the body may be used to maintain balance. In quiet stance, the body controls movement using three main joint centers: the ankle, the knee, and the hip. Depending on the terrain and task at hand, the body may shift its reliance on or away from an individual joint and increase its use of another. Thus, the ability to maintain balance is contingent on the body's ability to contract muscles throughout the lower limbs and trunk.

Together, sensation, cognitive processing, and biomechanical action afford us the ability to interact with our environment and get around safely, effectively, and efficiently.

2.2 Changes in Aging

Maintaining balance requires a fine-tuned combination of sensory, neural, and muscular subsystems; when any one of these subsystems is hindered, the weight of these damages can be felt throughout the entirety of the system. Perhaps the greatest threat to this system is aging. As we age, our body undergoes several changes that affect mobility, limiting our ability to get around safely. These changes are well-documented in many of our own family histories, as well as in medical textbooks under the term sarcopenia.

Sarcopenia refers to a myriad of biomechanical and neurological changes in the body as a direct result of aging. It is a geriatric syndrome that is most commonly defined as a gradual loss of muscle mass, strength, and quality in aging.[27] However, there are also a multitude of upstream neurological changes that are believed to contribute significantly to overall decline in health.[28,29] These are thought to include downregulation of essential neurotransmitters, impaired motor coordination, motor unit reorganization, chronic inflammation, and damage to neuromuscular junctions.[28] The combined effects of these changes are seen in decreased reaction times, dampened sensory sensitivity, inaccurate estimation of body position, and so on.[30–32]

Due to these physiological changes in aging, accidental falls are the number one cause of injury-related death in adults aged 65 and older.[1] Of those that survive serious falls, an estimated 7 million result in injuries that require medical attention, amounting to over $50 billion in medical expenses every year.[1–3] Not only do fallers frequently endure intensive medical treatments and rehabilitation, they often face lasting detrimental effects to their mobility, limiting physical activity and increasing the likelihood of future falls.[4] In fact, in a study of 325 older adults, 57% of subjects

that had a fall in the previous year experienced at least one new fall, 31% suffered two or more falls, and 19% survived 3 or more falls over the course of the next twelve months.[4]

2.3 Clinical Fall Risk

Because of the prevalence of falls in older adults, clinicians have developed a myriad of tests to assess an individual's overall fall risk. Tests can range from a review of medical history and survey-based evaluations to performance-based physical tasks. The Centers for Disease Control and Prevention (CDC) has established a list of factors that are known to contribute to an increased risk of falls, called the Stopping Elderly Accidents, Deaths, & Injuries (STEADI) Fall Risk Checklist.[33] This checklist details a variety of risk sources, including a history of falls, confounding medical conditions, medication type and dosage, vision acuity, blood pressure, and performance on clinical balance tests like the Timed Up and Go (TUG).

Checklists like this can be a helpful touchpoint for some older individuals, but often lack the sensitivity to accurately assess fall risk, especially for individuals in the earlier stages of balance deficit, before the first fall. In fact, one of the most accurate predictors of future falls is a history of falls, a metric that is neither effective for first-time fallers nor an indicator of the underlying biomechanical changes that ultimately lead to a fall.[34,35] Even with significant medical advancements in the past several decades, fall risk, and how to properly assess it, remains overwhelmingly ambiguous.

2.4 Postural Sway

Outside of the clinical realm, balance has also been studied by basic scientists and researchers that seek to understand movement from a mechanistic perspective. One of the most common ways to study balance is through the measurement of the center-of-pressure (COP), the location of the sum of forces between the body and the ground surface.[36] To gather this data, subjects stand on a force

plate, which measures forces and moments in the vertical, anteroposterior (AP, front-back), and mediolateral (ML, side-side) directions. COP is then calculated according to Equations 1 and 2, where M represents the moment, F represents the force, and d_z is the distance between the top force plate surface and the internal measurement device, as defined by manufacturer specifications.[36]

(Eq 1.) $$COP_{ML} = -\frac{M_{AP} + F_{ML} * d_z}{F_z}$$

(Eq 2.) $$COP_{AP} = \frac{M_{ML} - F_{AP} * d_z}{F_z}$$

M: Moment
F: Force
d_z: Manufacturer specification

This type of measurement is typically done over a series of time, tracking the location of the COP for anywhere from 10 seconds to 10 minutes (or longer) and forming what's known as a stabilogram (Figure 3).

From these stabilograms, we can extract measures that describe different attributes of the plot, such as the range of values, the overall size, or how fast it moves.[37] It is also possible to extract nonlinear measures that describe more complex characteristics of the plot, such as predictability and variability.[38] Some common measures of COP can be found in Table 2.

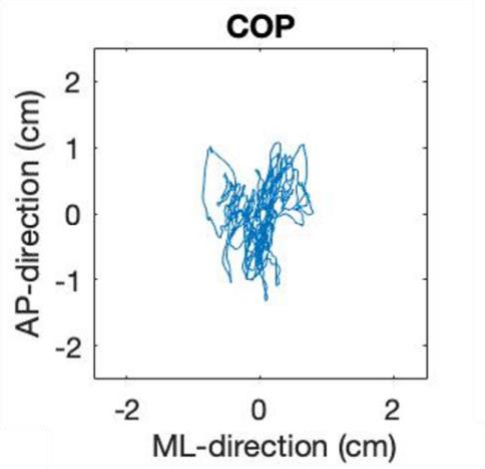

Figure 3. Example of a stabilogram, which depicts movement of the center-of-pressure (COP) over 60 seconds in the mediolateral (ML) and anteroposterior (AP) directions

Table 2. Summary of common measures of center-of-pressure

	Measure	Description
Linear	Range	Distance between the maximum and minimum value in the AP or ML direction[39]
	Path length	Total distance traveled by the COP[39]
	Velocity	First derivative of position; can be calculated as the mean or maximum value[39]
	95% Ellipse	Area of the stabilogram, defined as the region that encapsulates 95% of the COP data[40]
	Root-mean-square (RMS)	Dispersion or variability of the COP signal; can be calculated on the COP data itself, or COP velocity[39]
Nonlinear	Entropy	Regularity or predictability of the COP signal; various methods include Sample, Multiscale, and Approximate[41,42]
	Lyapunov exponent	Local stability of the COP signal; the rate of separation between datapoints[38,43]
	Detrended fluctuation analysis (DFA) alpha	Complexity of the COP signal; statistical self-similarity or fractality[44]

Rambling-Trembling Decomposition

Origins and Interpretation

Extending COP analysis further, Zatsiorsky & Duarte (1999) developed a novel method called rambling-trembling (RM-TR) decomposition. This method takes any COP time series and "decomposes" it into two distinct components: RM, which represents large-scale movement of an equilibrium point, and TR, oscillations around this point.[45] Zatsiorsky & Duarte were not the first to theorize the presence of a moving reference point; the study of postural control predates the modern computer and has resulted in a seemingly infinite number of proposed theories to explain sway and its driving forces. Perhaps the most closely related hypothesis is the λ model, developed by Asatryan & Feldman in 1965.[46] Both theories rely on the identification of an equilibrium point set by the body to maintain stability, but these theories differ by one key distinction: the

equilibrium point determined in the λ model is defined using kinematic joint position, whereas the RM-TR hypothesis defines it based on the balance of forces.[45] Regardless of the exact methodology, there is value in identifying the location (and movement) of the body's ever-changing equilibrium point.

By separating COP into these different time series, RM-TR decomposition seeks to understand postural control from a mechanistic perspective by sorting components of motion into their respective subsystems. As noted, maintaining human balance is an incredibly complex task, with a multitude of input sources and control mechanisms that, together, achieve postural stability. Traditional COP analysis is limited in its ability to capture the influence of these individual factors, but RM-TR decomposition begins to parse out these contributions. Though RM-TR cannot identify distinct neuromuscular control loops, it can distinguish attributes of sway that may be linked to their driving control subsystem. RM is thought to represent the body's equilibrium trajectory, or reference point, constantly moving and resetting, even in quiet stance. TR, on the other hand, is reminiscent of forces determined by intrinsic, pseudo-elastic musculoskeletal properties.[45]

Some scientists have gone as far as to attribute RM and TR components of sway to the central and peripheral nervous systems (or supraspinal and spinal), respectively. Shin et al. (2019) studied the contractile properties of skeletal muscle in healthy young adults and found that muscle stiffness and contraction time (peripheral musculoskeletal properties) were both significantly correlated with behavior of the TR component.[47] This relationship is further supported by Bolbecker et al. (2018), which found that RM was strongly linked to visuomotor processing (a function performed by the central nervous system).[48] Though this relationship to the nervous system remains a mere hypothesis, there is still much to learn from decomposing the COP.

Mathematical Calculation

Despite the complex nature of the underlying RM and TR mechanisms, the calculation methodology is relatively simple, requiring only three steps:

a) Find instances when the horizontal force, $F_{hor} = 0$, known as instant equilibrium points (IEPs).

b) Plot COP values at identified IEPs and interpolate points using a cubic spline function. This interpolated time series represents an estimation of the rambling trajectory.

c) Subtract COP from the rambling trajectory to estimate the trembling time series.

Graphical depictions of these three steps are shown in Figure 4, with steps a-c corresponding to subplots a-c.

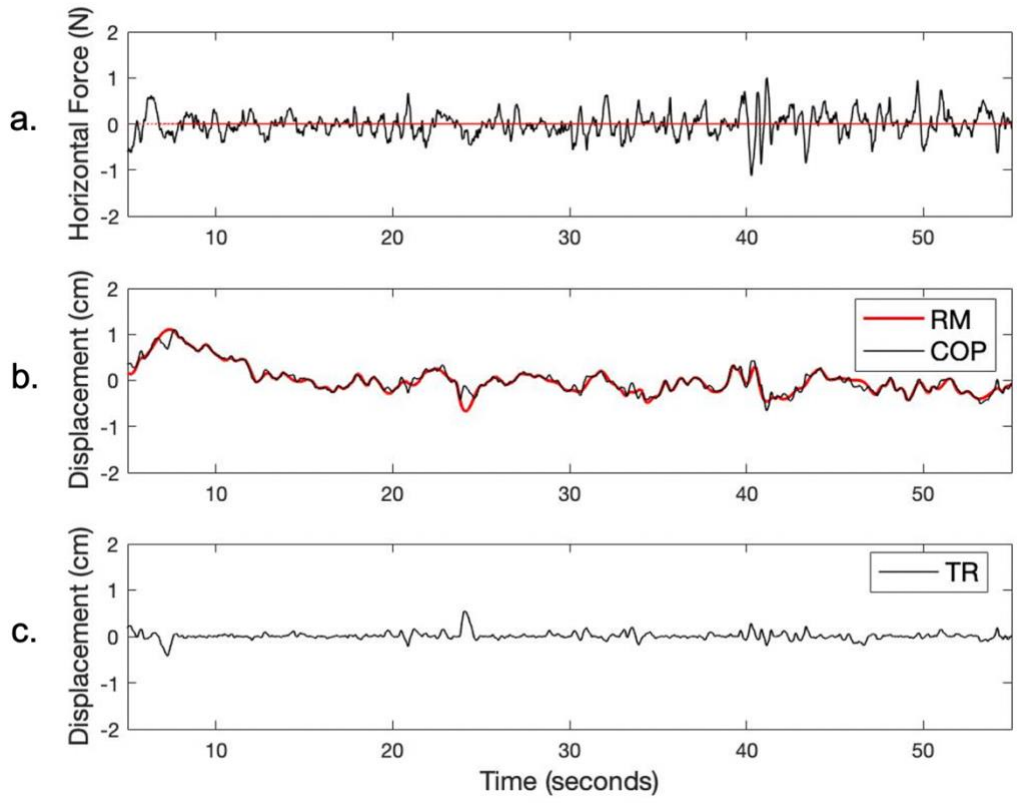

Figure 4. Representative depiction of the rambling-trembling (RM-TR) decomposition process

RM-TR decomposition results in two new, distinct time series. An example of the resulting spatial stabilograms (in the AP and ML directions) are depicted in Figure 5. From these time series, traditional COP measures, such as range, root-mean-square, or sample entropy can be extracted. From there, we can compare the effects of various pathologies or experimental conditions within and between COP, RM, and TR components. Because these time series are not entirely independent (because they were calculated based on the same COP time series), statistical analysis between COP, RM, and TR outcome measures must include a model that takes this into account, such as that established in a repeated measures analysis of variance.

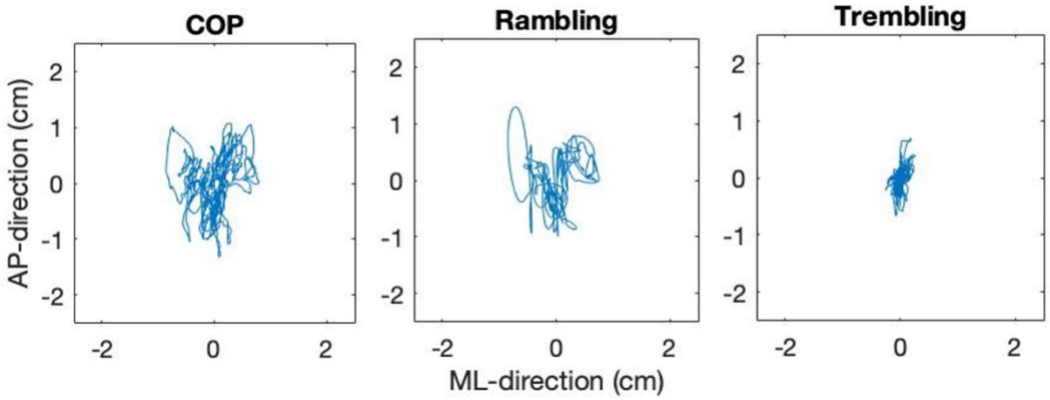

Figure 5. Representative plots of center-of-pressure (COP), rambling (RM), and trembling (TR) time series

2.5 Gap in Knowledge

There is much room for improvement in the realm of clinical fall risk detection. Existing methods fail to identify fall risk in a significant portion of older individuals, leaving them unknowingly vulnerable to potentially life-altering falls. These failures are especially prominent in earlier stages of fall risk, when the physiological changes that accompany healthy aging, such as decreased sensation and muscle loss, are relatively subtle. The earlier one is able to identify fall risk, the better they will be able to prevent future falls and reduce the likelihood of experiencing a vicious feedback loop of injuries, falls, and repeat injuries of increasing severity.

The study of postural sway has the potential to inform fall risk detection methodologies. In fact, Mancini & Horak have directly identified posturography as a potential remedy to the shortcomings of existing clinical balance assessment.[49] However, there is still much left to explore regarding appropriate outcome measures that demonstrate sufficient sensitivity to changes in balance as a result of injury, disease, or aging. COP has been studied extensively under this framework, but the search for the "holy grail" of outcome measures has remained relatively unfruitful.

Rambling-trembling decomposition offers a unique addition to the study of postural sway, linking components of movement to potential underlying subsystems that dictate them. Several studies have examined the influence of various conditions such as drug use, spinal cord injury, aging, and multiple sclerosis, but investigation of RM-TR behavior specifically with respect to sensory loss, a critical component of age-related balance decline, is limited.[10,11,48,50] Therefore, the primary goal of this work is to further our understanding of sensation (or lack thereof) under the rambling-trembling framework. Long-term, it is expected that this work will contribute to the advancement of clinical balance assessment, ultimately aiding in clinical fall risk detection and improving overall quality of life with age.

Chapter 3: Predictability of Rambling-Trembling Sway: Effects of Simulated Progressive Somatosensory Deficit in Healthy Young Adults

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Abstract

One of the primary contributors to falls in older adults is somatosensory degeneration. A method of center-of-pressure (COP) analysis, rambling-trembling (RM-TR) decomposition, has the potential to significantly improve balance deficit detection. However, its ability to capture sensation-based changes to postural sway is not well understood. Therefore, the objective of this study is to quantify the effects of progressive, simulated somatosensory deficit on COP, RM and TR time series. Fifty-one healthy adults (aged 22.10 ±1.88 years) completed three 60-second quiet standing trials with eyes closed for each randomly-ordered foam thickness condition (no foam, 1/8″, 1/4″, 1/2″, and 1″). Foot-floor kinetic data was collected at 100 Hz using two 6-axis force plates and a 16-bit A/D acquisition system. The data were filtered with a 10 Hz low-pass Butterworth filter and used to calculate COP, RM and TR time series. Range, root-mean-square (RMS), and sample entropy (SampEn) were calculated for each time series. Repeated measures analyses of variance, with $\alpha = 0.05$, were conducted. Range and RMS increased across foam thickness while SampEn decreased. TR showed the greatest magnitude of sample entropy ($p<0.001$), compared to COP and RM. Our findings suggest that RM-TR methods are able to isolate distinct biomechanical contributions to postural sway that are influenced independently by somatosensation. Future work should continue to explore the utility of RM-TR decomposition, including within the aging population, in order to advance our understanding of the role of sensation in postural control and assess its viability as a clinical tool.

Keywords: Center of pressure; Postural control; Rambling-Trembling; Falls; Nonlinear analysis

3.1. Introduction

In the United States, 28.7% of adults aged 65 or older experience at least one fall every year, amounting to an estimated 29 million falls.[51] Efforts have been made to identify fall risk in older adults, but a significant portion of the population remains unknowingly vulnerable to falls due to the limitations of current clinical assessment techniques. In fact, there remains an estimated 8-12% risk of fall over the course of the year for individuals with no identifiable risk factors.[34,52]

As we age, our bodies experience a multitude of changes that ultimately result in a progressive decline in physiological function.[27,30] Of these changes, perhaps one of the most prominent is somatosensory loss. Somatosensation allows us to perceive environmental and proprioceptive cues that inform postural adjustments, maintain balance, and move safely and efficiently.[53,54] As functionality of this system declines, the risk of severe falls, injury, and death increase substantially.[31,55]

To address the prevalence of falls in older adults and remedy the limitations of existing clinical assessment techniques, many researchers have attempted to quantify balance by measuring movement of the body's center-of-pressure (COP).[36] COP analysis has been used extensively in the study of human balance, including in investigations of aging and disease, but is limited in its clinical implications due to the uncertainty in its link to the underlying physiological mechanisms that dictate it.[56] Because of this disconnect, many of these analyses lack the reliability and sensitivity, on a patient-by-patient basis, to capture age-related balance changes, especially those that occur prior to the first fall.[40,57,58]

Rambling-trembling (RM-TR) decomposition of the COP has the potential to significantly improve balance deficit detection due to its proposed neurological link to postural control, segmenting the COP into an equilibrium point, RM, and oscillations around this point, TR.[10,12,45,59]

RM is thought to represent the body's equilibrium trajectory, or reference point, constantly moving and resetting, even in quiet stance. TR, on the other hand, is reminiscent of forces determined by intrinsic, pseudo-elastic musculoskeletal properties.[45] Some scientists have gone as far as to attribute RM and TR components of sway to the central and peripheral nervous systems (or supraspinal and spinal), respectively.[12,48,50] Due to these potential neuromotor links, the insights provided by RM-TR decomposition could advance our ability to identify fall risk in older adults and those suffering from somatosensory loss, but additional research is needed.

Previous work has indicated the presence of distinct sway behavior between COP, RM, and TR time series, with substantial differences in sensitivity based on severity of simulated deficit.[60] However, additional analyses are needed to further understand these time series and their empirical and clinical value in this application. One such method is nonlinear analysis, in which the system dynamics are assessed in terms of their temporal and frequency structures.[61] Sample entropy (SampEn) is a commonly used nonlinear measure of human movement, describing the predictability, or regularity of the system.[62] Under this framework, increasing SampEn values signify decreasing system predictability and decreasing values imply increasing predictability. This measure has shown success in its ability to distinguish healthy versus pathological conditions and thus shows promise in fall risk assessment.[41,43,44] Therefore, this study will serve as an expansion of Gerber et al., 2022, with special attention to SampEn, in the hopes of identifying changes to the center of pressure based on somatosensory input.

The objective of this study is to quantify the COP, RM and TR time series using measures of range, variability (root-mean-square, RMS), and predictability (SampEn) across various levels of simulated somatosensory deficit. It is hypothesized that (1.a) range, (1.b) variability, and (1.c) predictability will increase with foam thickness for all time series and (2) TR will demonstrate the

lowest range, variability, and predictability compared to COP and RM. We believe that these findings will contribute significantly to the body of knowledge regarding postural control and inform future fall risk assessment strategies.

3.2. Materials and Methods

3.2.1 Participants

Fifty-two healthy young adults (aged 22.10 ± 1.88 years, 23 females) volunteered to participate in the study. All participants were informed of the study risks and benefits, and provided written consent, as approved by the University of Kansas Institutional Review Board. Participants with a history of neurological disorder, balance impairments, and/or significant injury to the trunk or lower limbs were excluded from the study. One subject was removed from the study due to significant deviation from outcome measure means (>3σ), resulting in a final sample size of 51.

3.2.2 Experimental Conditions

Participants stood naturally, with arms at the sides, eyes closed, head upright, and a standardized stance width of 17cm and a 20° angle between feet.[63] Five randomly-ordered foam thickness conditions (no foam, 1/8", 1/4", 1/2", and 1", corresponding to F0, F1, F2, F3, and F4, respectively) were used to simulate increasing severity of somatosensory deficit. Foam pads were 12"x12" with a density of 2 lbf/ft^3 and pressure to compress 25% of 4 psi (McMaster-Carr, Chicago, IL). Experimental foam thicknesses were selected based on commercial availability as to avoid the need for stacking and subsequent material property discontinuities or potential slippage during testing. Three 60-second trials were completed for every foam condition, with 5-minute seated breaks every six trials.

3.2.3 Data Collection and Analysis

Foot-floor kinetic data was collected at 100 Hz using two 6-axis AMTI force plates (Watertown, MA, USA) and a 16-bit A/D acquisition system (Cambridge Electronic Design, Cambridge, England, UK). Using MATLAB software (Mathworks, Natick, MA), data were filtered with a 2nd order 10 Hz low-pass Butterworth filter and used to calculate COP.[36]

Force and COP position trajectories were then used to calculate RM and TR time series in the AP and ML directions, as detailed by Zatsiorsky & Duarte (1999).[45] As delineated in this study, COP positions at instant equilibrium points, the time when horizontal force (F_{hor}) = 0, were found and interpolated using a cubic spline function to estimate RM trajectory. The RM trajectory was subtracted from the COP to calculate the TR trajectory. For simplicity, these three distinct time series will be referred to as COP, RM, and TR.

From these time series, three primary measures were calculated: (1) range, (2) root-mean-square (RMS), and (3) sample entropy (SampEn). Based on recommendations from Nichols (2020), SampEn input parameters were set to m = 2 and r = 0.0986.[64] Calculations for each measure were done independently in the AP- and ML-directions and for each level of foam thickness. Table 1 provides a convenient key to acronyms referenced throughout this work.

3.2.4 Statistical Analysis

With 95% power and an effect size of 0.25, the minimum sample size for this study was estimated to be 45 participants, which was exceeded during recruitment. MATLAB software (MathWorks, Natick, MA) was used to perform repeated measure analyses of variance (ANOVA). Tukey's HSD post hoc tests were used to determine statistical significance among foam thicknesses (F1-F4) and measure types (COP, RM, or TR). Statistical significance for each test was set to $\alpha = 0.05$.

3.3. Results

Significant differences (p<0.001) were found when comparing between COP, RM, and TR measures at every foam thickness. Figures 6-8 depict the average range, RMS, and SampEn values for each foam condition in the AP- and ML-directions for COP, RM, and TR time series, respectively. Standard deviations are shown using error bars and significant differences (p<0.05) between foam thicknesses are shown using brackets and asterisks (*). In general, range and RMS increased across foam thickness for all time series, while SampEn decreased.

3.3.1 Range

In the AP-direction, the COP and RM time series showed significant increases between average ranges in F0 and F1-F4, F1 and F2-F4, and F2 and F4 (Figures 6a, 7a). In the ML-direction for COP and RM, these differences were found between F0 and F2-F4, F1 and F3-F4, and F2 and F4 (Figures 6b, 7b). For TR in the AP-direction, significant increases in range were found for F0 and F1-F4, F1 and F2-F4, F2 and F4, and F3 and F4 (Figure 8a). In the ML-direction, TR showed significant differences between F4 and F1-F3 (Figure 8b).

3.3.2 Root-Mean-Square (RMS)

In the AP-direction, the COP and RM time series showed significant increases in average RMS values between F0 and F2-F4, F1 and F2-F4, and F2 and F4 (Figures 6c, 7c). In the ML-direction for COP and RM, significant increases were found between F0 and F2-F4, F1 and F2-F4, and F2 and F4 (Figures 6d, 7d). For TR in the AP-direction, significant differences in RMS were found between F0 and F2-F4, F1 and F3, and F4 and F1-F3 (Figure 8c). In the ML-direction, TR showed significantly different RMS values between F4 and F0-F2 (Figure 8d).

3.3.3 Sample Entropy (SampEn)

In the AP-direction, the COP time series showed significant decreases between average SampEn values in F0 and F2-F3, and F1 and F2-F3 (Figure 6e). In the ML-direction for the COP time series, significant decreases were found between F0 and F2-F4 and F1 and F4 (Figure 6f). For the RM time series in the AP-direction, only F0 and F2-3 showed significantly different SampEn (Figure 2e). In the ML-direction, a significant decrease was found between F0 and F2 (Figure 7f). For TR in the AP-direction, significant differences were found for F0 and F2-F4, and F4 and F1-3 (Figure 8e). In the ML-direction, significant differences were found for F0 and F3-F4, F1 and F3-F4, and F4 and F2-F3 (Figure 8f).

3.4. Discussion

The purpose of this study was to quantify the influence of simulated somatosensory deficit on measures of sway range, variability, and predictability. The first hypothesis, which stated that range, variability, and predictability would increase across foam thickness for the COP, RM, and TR time series, was supported. This effect was observed in both the AP- and ML-directions. Predictability was assessed using SampEn; the decrease in SampEn across foam thickness implies less systemic entropy, indicating an increase in overall signal predictability. Variability (RMS) and range showed similar increases across simulated deficit severity. These findings are consistent with existing studies; foam has been shown to introduce a degree of postural instability, even in healthy young individuals, due to its viscoelastic mechanical properties and subsequent dampening of touch feedback at the plantar surface.[13,65–67] This observed effect supports the use of foam as a model for aging, with these foam-induced changes mirroring common characteristics of sway in older adults.[68,69]

However, it is important to note that, despite mimicking many age-linked biomechanical changes to sway, the use of foam remains a rudimentary model for aging. In this study, increasing foam thickness was a simple, quantifiable means to model incrementally worsening somatosensory deficit. The overarching goal was to investigate the influence of progressive sensory loss within an individual subject, an insight nearly impossible to capture without simulated deficit (like that utilized in this study) or a multi-year longitudinal study with extensive inclusion/exclusion criteria. Though they provided many insightful learnings on the influence of somatosensation on balance, the results of this work are inherently limited in their generalizability to the elderly population. Thus, future work should incorporate a true sample of older adults with progressively worsening balance (e.g. non-fallers, history of falls, frequent fallers), using these findings to inform experimental design, analysis methodology, and interpretation.

The second hypothesis stated that, compared to COP and RM, the TR time series would show the lowest range, variability, and predictability. This hypothesis was supported, with significant differences between TR, COP, and RM for all measures and differing trends across foam thickness.

AP and ML range in the COP, RM, and TR time series increased steadily with increasing foam thickness. In the AP-direction, COP and RM showed similar levels of significance between foam levels, presenting significant differences in as little as 1/8” of foam thickness (F0 versus F1), but not between F3 and F4, a thickness difference of 1/2". Conversely, TR AP range showed no significant difference between F0 and F1, but did find F3 and F4 to be different. For COP and RM, AP variability (RMS) was shown to increase across foam thickness, but F3 and F4 showed no significant differences, suggesting a plateau in this effect beyond 1/2" of foam. Prior to F3 (1/2” of foam), AP RMS appeared to increase incrementally with foam thickness. This observation is

found also within SampEn measures. Neither COP nor RM showed significant differences in AP SampEn between F0 and F4, a comparison that, assuming linearity of simulation effect, was expected to show the highest level of contrast. Instead, COP and RM AP SampEn appear to plateau after F1, even showing a slight increase in mean values between F3 and F4. This trend is found also in RM ML SampEn, but not in COP ML SampEn, which follows a more incremental decrease across foam thickness, as expected.

It is not clear why the effects of increasing foam thickness would dissipate beyond 1/2", but two possible explanations to this observation include (1) a ceiling effect, in which the amount of system variability is saturated, reaching a relative maximum by F3, and/or (2) given the mechanical properties of foam and high level of surface instability, the body recruits altered control mechanisms that attempt to minimize sway variability.

It is well-documented that, depending on the biomechanical challenge, the body relies on different joint strategies to maintain balance.[70] For example, Gatev et al. (1999) demonstrated that in quiet standing, the ankle is primarily responsible for postural control in the AP-direction, but reducing stance width shifts this responsibility onto the hip.[71] Fasola et al. (2019) noted that, when ankle motion was restricted, subjects heavily relied on flexion and extension of the knee to control the center of mass; in more extreme deviations, the trunk was recruited to oppose motion and correct posture.[72] Riemann et al. (2003) demonstrated that the ankle remains the primary contributor to balance on both stable and unstable support surfaces, such as foam, but noted the increase in importance of proximal joints, including the hip and knee.[73] Therefore, it is not unfounded to suggest that the observed plateau may be a result of a shift in joint-based postural control strategy at greater foam thicknesses. This would further support the use of foam as an aging model, especially at greater thicknesses, because this shift in joint strategy is also observed in older

individuals, who are increasingly reliant on proximal joints.[74] However, additional experimental methodologies, such as motion capture or electromyography would be required to support this conclusion.

The TR time series SampEn demonstrated the greatest sensitivity to changes in foam thickness, presenting considerably more significant differences between foam conditions than either COP or RM. While many COP and RM measures tended to plateau beyond F3, TR SampEn scaled relatively proportionally with foam thickness, a measure characteristic that is highly desirable for tracking an individual's balance deficit over time. Additionally, the large overall magnitude of TR SampEn suggests that, although only a small portion of overall sway, the TR time series contributes substantially to system predictability (or lack thereof). Thus, TR SampEn may serve as a powerful measure of balance deficit, especially for those suffering from somatosensory loss. This is echoed in previous work, which found ML TR to be highly sensitive to simulated somatosensory deficit, exceeding a 20% increase in maximum jerk between no foam and 1" foam conditions, whereas COP experienced similar plateaus at greater foam thicknesses.[60] These results are expounded by findings of the present study, further highlighting the unique value that each of these time series may provide in the study of human balance and in clinical fall risk assessment.

Despite these promising findings, this study remains limited by selected outcome variables of sway range, RMS, and SampEn. These measures were carefully chosen, given their prominence in the study of aging, but there remains a wealth of unexplored sway measures and alternative methodologies, such as electromyography, that could contribute additional value to this work. Therefore, future studies should incorporate these learnings while continuing to explore a wide variety of measures to fully quantify the complex dynamic between sensation and postural control.

The study of balance is vital to both furthering our understanding of biomechanical control mechanisms and to improving fall risk assessment techniques. Somatosensory decline poses a significant risk to the aging population, reducing the accessibility of critical environmental and proprioceptive cues. The findings of this study highlight the scientific value of rambling-trembling methodology, examining sway from a mechanistic perspective and providing new, clinically-relevant insights into postural control. Though there is much work to be done to fully comprehend the utility of rambling-trembling, it shows tremendous promise in its ability to identify and track the progression of somatosensory deficit.

Conflict of Interest Statement

The authors declare no conflict of interest.

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Tables and Figures

Table 3. Common acronyms used throughout analysis

Acronym	Variable
AP	Anteroposterior direction (front-back)
ML	Mediolateral direction (side-side)
RMS	Root-mean-square
SampEn	Sample entropy
COP	Center-of-pressure time series
RM	Rambling time series
TR	Trembling time series
F0	Baseline foam condition (no foam)
F1	1/8” of foam
F2	1/4" of foam
F3	1/2" of foam
F4	1” of foam

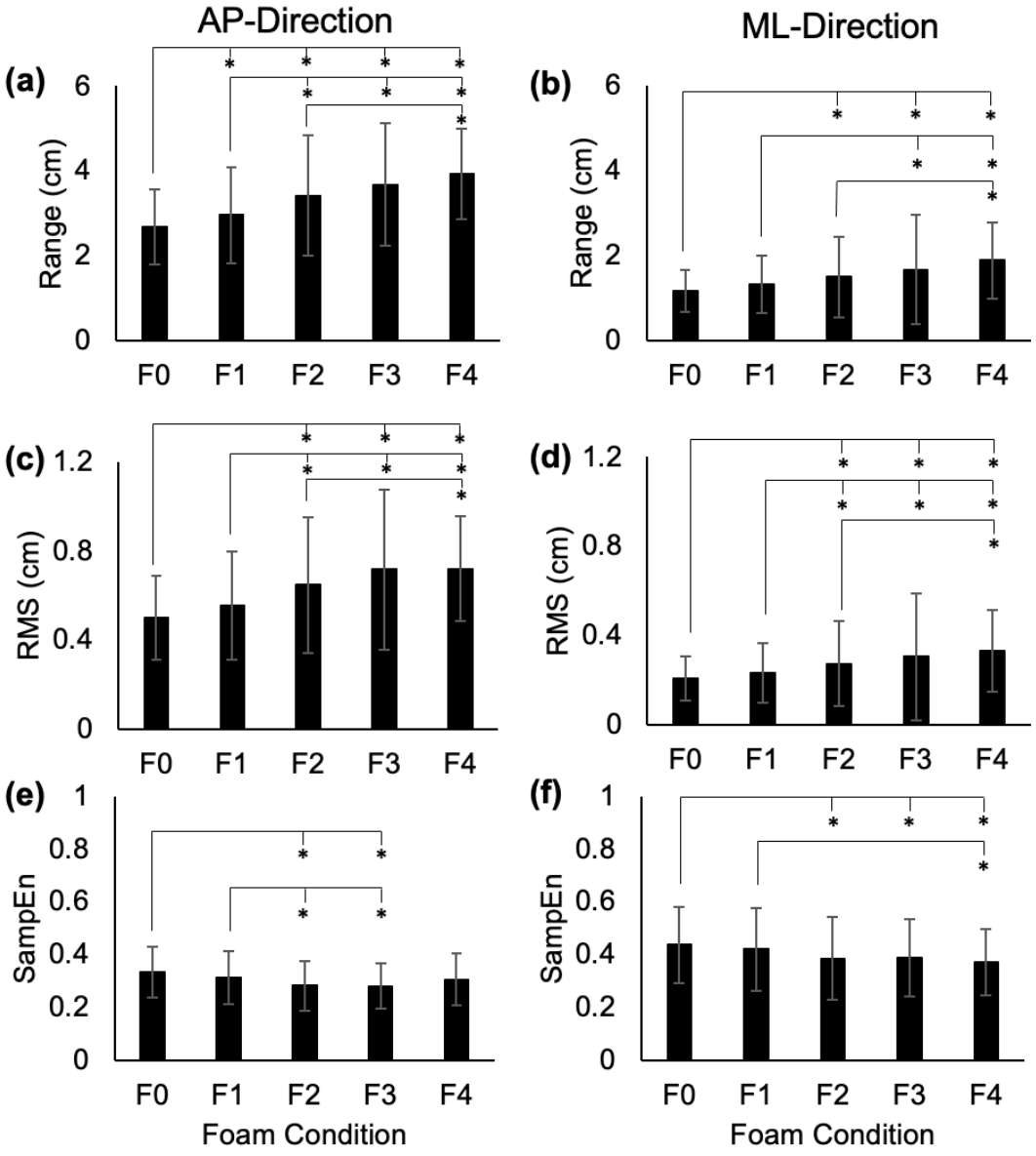

Figure 6. Range, RMS, and SampEn for the COP time series in the AP and ML directions. Error bars represent standard deviations. Significant differences (p<0.05) are shown with an asterisk (*).

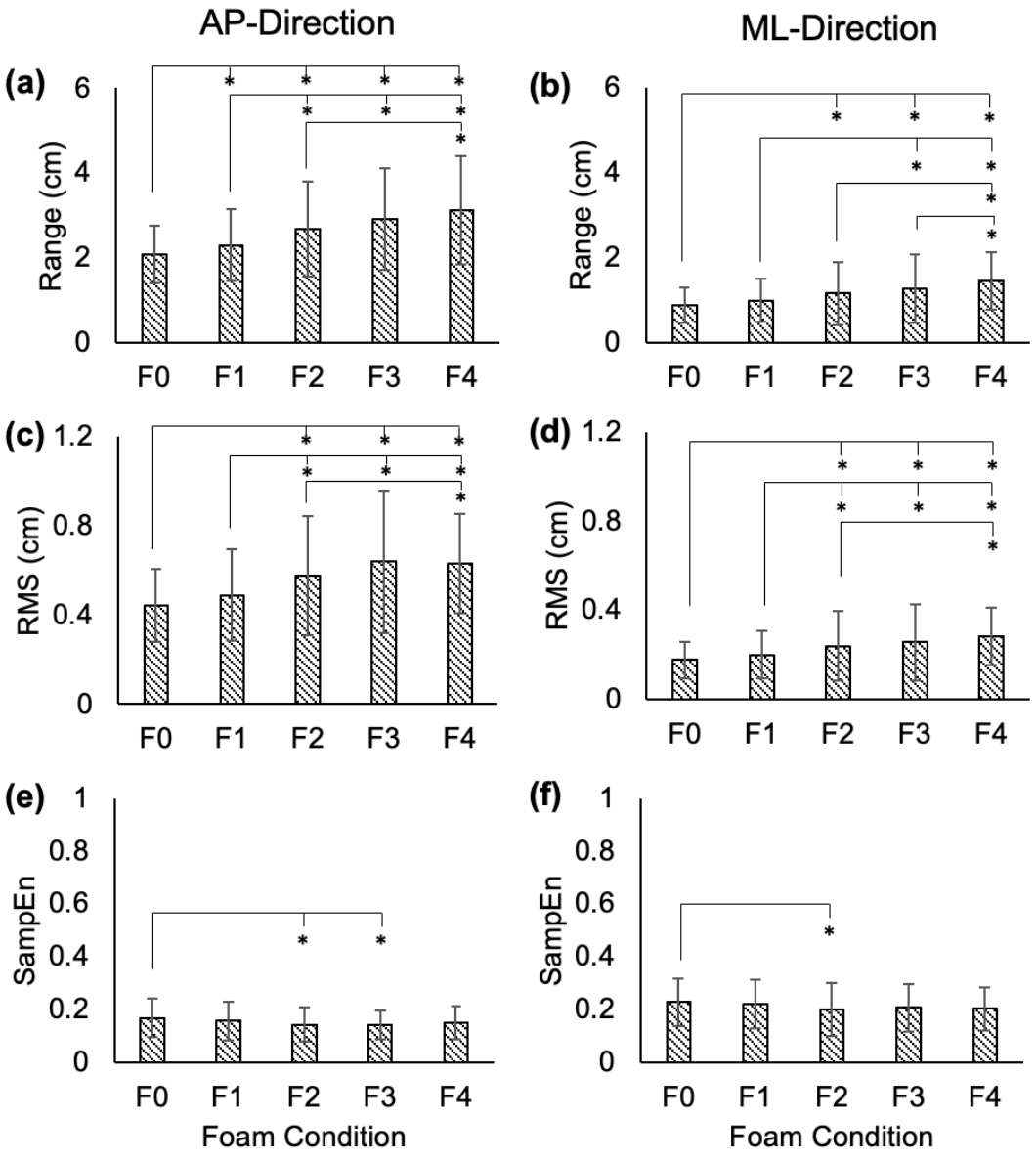

Figure 7. Range, RMS, and SampEn for the RM time series in the AP and ML directions. Error bars represent standard deviations. Significant differences (p<0.05) are shown with an asterisk (*).

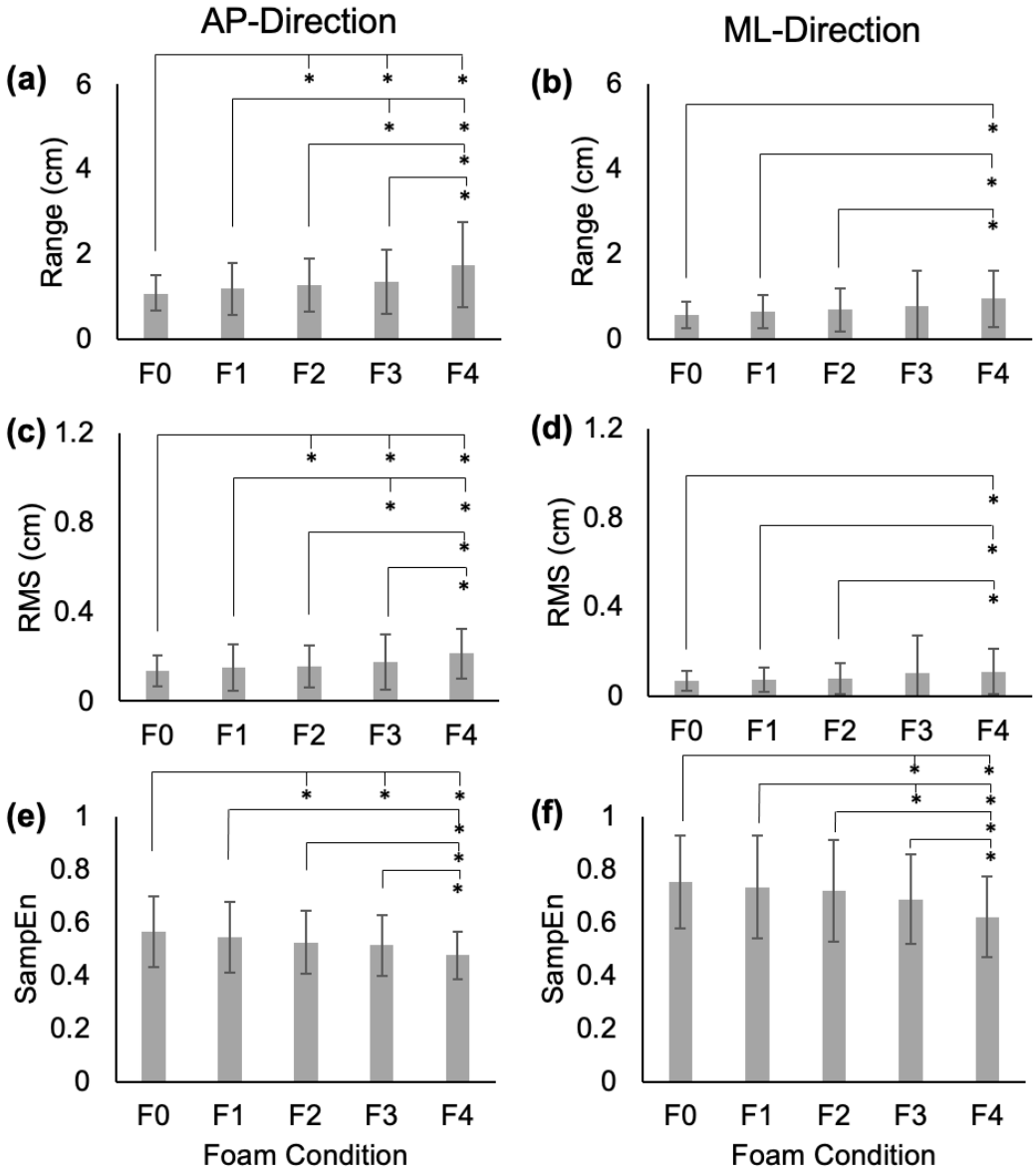

Figure 8. Range, RMS, and SampEn for the TR time series in the AP and ML directions. Error bars represent standard deviations. Significant differences (p<0.05) are shown with an asterisk (*).

Chapter 4: A mechanistic approach to the Sensory Organization Test – the influence of somatosensation, vision, and vestibular sense on rambling-trembling sway

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Highlights:

- Sensory re-weighting requires distinct rambling and trembling sway adaptations
- Spinal postural control mechanisms are greatly influenced by sensory conflict
- Rambling-trembling decomposition may be able to differentiate balance deficits by their sources

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Note: Manuscript has been prepared to align with the submission guidelines for Gait & Posture

Abstract

Background: Implementation of The Sensory Organization Test (SOT) under the rambling-trembling (RM-TR) framework allows for an examination of both individual sensory contributions and compensatory mechanisms, an incredibly valuable insight in both research and clinical settings. Such investigation could add substantial power to our ability to assess and treat fall risk in older adults and those suffering from neurological disorders.

Research Question: How are RM and TR components of sway influenced by SOT-induced challenges in healthy adults?

Methods: Twenty-three healthy adults volunteered to participate in this study. Each participant completed a VR-based SOT program, which included 6 conditions with varied visual environments (normal, blacked-out, conflict) and support surfaces (stable, unstable foam), while a force plate captured forces at the plantar surface. Center of pressure (COP) was calculated and decomposed into RM-TR components. For each time series, range, root-mean-square (RMS) and sample entropy (SampEn) were extracted. Individual contributions of somatosensation, vision, and vestibular sense, as well as the preference ratio, were calculated. Repeated measures ANOVA were used to compare the effects of time series type (COP, RM, TR) and SOT condition. Paired t-tests were used to assess the difference in preference ratio between RM and TR components.

Results and Significance: TR sway behavior was impacted significantly by the sensory challenges induced by the SOT procedure, while RM was largely unaffected. Such findings are characteristic of healthy individuals, capable of competently re-weighting sensory input, but still facing challenge-based adaptations. Additionally, the ML SampEn preference ratio was significantly higher in TR compared to RM, indicating potential differences in compensation strategies between supraspinal and spinal/peripheral control mechanisms. Findings from this work

serve as a foundation for future RM-TR analyses using SOT procedures, aiding in our ability to implement targeted diagnostic and treatment methods, ultimately reducing the incidence of falls in aging and pathologic populations.

Keywords: Sensory Organization Test; rambling-trembling; center of pressure; sample entropy; postural sway

4.1. Introduction

Somatosensation, vestibular sense, and vision are all known to contribute to postural sway.[75,76] The body is constantly using input from each of these senses to determine its position in space and make corrections as needed. Although the senses are often studied as distinct entities, there is a large degree of interdependence and input modulation required to maintain balance. Error can be introduced into the system when sensory input sources provide conflicting or missing information about the surroundings. This can occur for a variety of reasons, including disease, trauma, or general sensory decline due to aging. In this case, the nervous system must consider the reliability of incoming information and re-weight its importance to resolve the sensory conflict. This process of sensory re-weighting is commonly acknowledged in the literature, but the underlying biomechanical effects and mechanisms by which the body achieves conflict resolution remain largely unknown.[5,77,78]

To study this, researchers and clinicians have developed a protocol called the Sensory Organization Test (SOT) that aims to capture a comprehensive view of the role of sensation in balance from the perspective of both an individual sense and the integration of multiple senses. It accomplishes this by capturing postural sway during various system-manipulated conditions that alter the availability and reliability of sensory information from the support surface and visual environment. This test can be incredibly informative in both clinical and research applications, but is limited in its accessibility due to the need for expensive, specialized equipment such as the NeuroCom® SMART Equitest® system. As a commercial product, it also operates largely as a black-box system, leaving many quantitative analyses unexplored due to the limited availability of outcome measures. However, the ubiquity of virtual reality (VR) simulation has removed several of these barriers, making administration of this test more accessible than ever.[77,79] Moon

et al. (2021) developed and validated a novel, VR-based SOT method, called the VR Comprehensive Balance Assessment and Training (VR-ComBAT) system that mimics the NeuroCom® system using only a VR headset, foam, and a force plate.[77] These advancements allow for in-depth exploration of the senses, both as individual entities and as a multi-input feedback system.

Such exploration is further enhanced through the incorporation of rambling-trembling decomposition, an analytical method developed by Zatsiorsky & Duarte (1999) to isolate distinct components of the center of pressure (COP): rambling (RM), equilibrium (or reference) point motion and trembling (TR), oscillations around this point.[45] RM-TR methodology adds depth to traditional COP analyses, providing insight into the postural control mechanisms that dictate sway, a practice that is beneficial in both basic research and clinical settings. It accomplishes this by linking RM and TR components of sway to their proposed supraspinal and spinal/peripheral drivers, respectively.[9,10,12,80] Previous RM-TR studies have examined the effects of aging, somatosensory loss, and Parkinson's Disease, elucidating many of the underlying changes to sway under such conditions.[60,68,81] Costa et al. (2022), for example, found that individuals with Parkinson's Disease show changes to both RM and TR components, indicating impairments in sensorimotor integration (caused by the characteristic Parkinsonian decline in dopaminergic neuron activity) and feedback processes that regulate muscle reflexive properties, respectively.[47,68,81] Similarly, Gerber et al. (2022a,b) demonstrated that dampening plantar somatosensory input in healthy adults affects primarily the TR component, disrupting sensory input and peripheral reflexes.[60,82] As exhibited in these studies and many more, RM-TR decomposition adds substantial interpretative value to traditional analyses and thus may further enhance insights from SOT methodologies.

Therefore, the primary objective of this work is to quantify the influence of both individual and integrated senses under the RM-TR framework using the novel VR-ComBAT system. There are two hypotheses for this study: (1) as task difficulty (condition number) increases, (1.a) range, (1.b) variability, and (1.c) predictability will increase and (2) vision will demonstrate a significant individual contribution to sway. One day, the insights provided by this work may inform targeted balance intervention strategies that improve clinical outcomes, mobility, and quality of life with age.

4.2. Methods

4.2.1 Participants

Twenty-three healthy participants (10 male, 13 female) with a mean age of 27.4 ± 8 years volunteered to participate in this study. Prior to participation, subjects were screened for any cognitive or balance impairment using a battery of clinical tests, including the Montreal Cognitive Assessment (MoCA), the Berg Balance Test and the Mini Balance Evaluation Systems Test (Mini-BESTest).[83–85] All participants were informed of risks and benefits of the study and provided written consent, as approved by the University of Kansas Medical Center Institutional Review Board.

4.2.2 Testing Conditions

In alignment with the established clinical SOT, participants completed three trials each of six sensory conditions in numerical order, as detailed in Figure 9 and in Moon et al. (2021).[77] These six conditions alter visual and support surface properties in order to isolate distinct contributions of the senses, as depicted in Table 4. Conditions 1-3 require the participant to stand on a stable, firm surface (directly on the force plate), while conditions 4-6 involve a piece of foam (Amazon

Basics Balance Pad for Exercise Training, 35 cm × 5 cm × 40 cm, density = 0.04 g/cm^3) between the feet and the force plate. Conditions 1 and 4 include typical eyes open vision, with the VR environment remaining stable, conditions 2 and 5 black out the visual environment (but participants keep their eyes open), and conditions 3 and 6 manipulate the visual field, creating a visual conflict, by rotating the VR environment in the anteroposterior direction at a maximum range of 20 degrees and velocity of 15 degrees/second. Participants completed three 20-second trials for each SOT condition with 5-second breaks between trials.

4.2.3 VR Technology

All visual conditions were achieved using a head-mounted VR headset (HTC VIVE Pro Eye, HTC, Taoyan, Taiwan) with two tracking sensors (Steam VR Base Stations, HTC, Taoyuan, Taiwan) and dual-OLED 3.5-inch displays. The VR environment was created in Unity 3D (version 2019.3.0; San Francisco, CA, United States) and consisted of three panels (front, left, and right of the participant) positioned at 90 degrees from one another, with a multi-colored triangular pattern to facilitate visual engagement with the environment. Figure 10 depicts the VR environment in the three visual conditions (eyes open, blacked-out, and unstable/conflict).

4.2.4 Data Collection and Analysis

During each of the SOT conditions, participants stood on an AMTI Optima force plate (AMTI, Watertown, MA, United States), which collected force and moment data at a sampling frequency of 200 Hz. The force plate and VR system were manually synchronized at the start of every trial.

Using MATLAB software (Mathworks, Natick, MA, United States), this data was filtered with a 4th order 10 Hz low-pass Butterworth filter and down-sampled to 50 Hz. The first and last second of each trial were trimmed to minimize initial and end effects such as participant anticipatory motion. Force and moment data were used to calculate the center of pressure time

series, which was then decomposed into rambling and trembling components.[36,45] From these three time series, range, root-mean-square (RMS), and sample entropy (SampEn) were computed in the anteroposterior (AP) and mediolateral (ML) directions. SampEn input parameters were set to m = 2 and r = 0.1.[64]

Table 4 shows each SOT condition and the primary sensory system utilized. Using established SOT condition comparisons, the ability to utilize somatosensory, visual, and vestibular systems were isolated by comparing condition 1 with conditions 2, 4, and 5, respectively.[86] Additionally, "preference" was calculated by comparing the average outcome value of conditions 3 and 6 by that of conditions 2 and 5. Preference describes one's dependence on visual information, even if incorrect, as induced by the VR headset in conditions 3 and 6.[86,87] To understand how the body compensates in conflict and explore the proportional relationships between RM and TR components, preference was also analyzed as a reduced mathematical ratio, dividing the average of conditions 3 and 6 by that of 2 and 5. Ratios greater than 1 represent a higher outcome measure magnitude with visual conflict, while values less than 1 indicate a larger outcome measure with blacked-out vision.

4.2.5 Statistical Analysis

All statistical analyses were performed using MATLAB software. A post hoc power analysis was performed on the dataset and it was determined to be adequately powered for the study, at 95% power. Repeated measures analyses of variance (ANOVA) with Tukey's post hoc tests were used to compare SOT conditions (condition 1-6) and time series (COP, RM, TR) for each outcome measure (AP & ML range, RMS, SampEn). Mathematically-reduced preference ratios (PR) for the RM and TR components were compared using paired t-tests for each outcome measure. Significance for all tests was set to alpha = 0.05.

4.3. Results

Figure 11 depicts the mean outcome measures for each time series (COP, RM, TR) and condition (cond 1-6). In general, conditions 4-6 resulted in higher range and RMS, and lower SampEn compared to conditions 1-3. Table 5 isolates the contributions of somatosensation, vision, vestibular sense, and preference to sway outcome measures.

4.3.1 Somatosensation (cond 2 versus cond 1)

No significant differences in range, RMS, or SampEn were found between conditions 1 and 2.

4.3.2 Vision (cond 4 versus cond 1)

AP and ML range was found to be significantly greater in condition 4 than condition 1 for the COP, RM, and TR time series. TR RMS in the AP and ML directions was significantly greater in condition 4 compared to condition 1. ML TR SampEn was significantly lower in condition 4 than condition 1.

4.3.3 Vestibular Sense (cond 5 versus cond 1)

AP and ML range were significantly greater in condition 5 than condition 1 for COP, RM, and TR time series. AP and ML TR RMS were significantly greater in condition 5 than condition 1. ML TR SampEn was significantly lower in condition 5 compared to condition 1.

4.3.4 Preference

No significant differences in range, RMS, or SampEn were found when comparing conditions 2+5 with conditions 3+6. However, when computing the PR, RM and TR ML SampEn were significantly different ($p = 0.016$), with RM less than 1 (0.95 ± 0.13) and TR above 1 (1.08 ± 0.21), as shown in Figure 12.

4.4. Discussion

The purpose of this study was to investigate the influence of somatosensation, vision, and vestibular sense on sway in healthy young individuals with respect to underlying rambling and trembling behaviors. There were two primary hypotheses for this work: (1) as task difficulty (condition number) increases, (1.a) range, (1.b) variability, and (1.c) predictability will increase and (2) vision will demonstrate a significant individual contribution to sway.

Hypothesis 1.a is supported by our findings, with AP and ML range consistently greater in conditions 4-6 compared to 1-3 for COP, RM, and TR time series. AP and ML TR RMS is significantly greater in conditions 4-6 compared to conditions 1-3, supporting hypothesis 1.b. COP and RM RMS in the AP-direction show no appreciable trends, but shows a noticeable (but statistically insignificant) increase in mean values across conditions in the ML-direction. Standard deviations of RMS were incredibly high, approaching, if not exceeding, the magnitude of the means themselves. There were no significant differences in AP SampEn, but ML TR SampEn was significantly lower in conditions 4-6 versus conditions 1-3, suggesting that this component of sway became more predictable, supporting hypothesis 1.c. Though there certainly appears to be increasing range, variability, and predictability with task difficulty, this trend is primarily observed in stable (conditions 1-3) versus unstable (conditions 4-6) support surfaces rather than proportionally across condition number.

Regarding hypothesis 1, the non-statistical significance of rambling outcome measures is equally as discerning as the significance found in the trembling component. The rambling component of sway remained largely unaffected by the challenges provoked by the six SOT conditions, an expected observation in a population with an intact ability to integrate and re-weight sensory input.[68] At the same time, nearly all measured characteristics of the trembling component

were impacted by these challenges, indicating dampened sensorimotor feedback and disrupted peripheral reflexive properties, as targeted in SOT methodology.[11,60,68] As such, there was a greater discrepancy between neuromotor planning and output as task difficulty increased, reducing overall motion precision.

Hypothesis 2 is supported by our findings, with reliance on vision resulting in significant increases in range, variability, and predictability, especially in the trembling time series. In fact, dependence on vision resulted in an increase of nearly a centimeter in TR range in both the AP and ML directions, increases in TR RMS of 0.1 (AP) and 0.2 (ML) centimeters, and a decrease in ML TR SampEn of 0.1. Vision has long been documented as highly influential to sway and motion in general.[17,19] Somewhat unexpectedly, this was true for vestibular sense as well, with significant differences (and magnitudes of outcome measures between conditions) mirroring those of the vision comparisons. For example, the reliance on vision and vestibular sense are both associated with an increase in AP RM range of approximately 0.6 cm. This suggests that in healthy young adults, vision and vestibular sense played near-equal roles in the modulation of quiet standing sway magnitude.

Visual conflict introduces an added layer of sensory challenge to the system, forcing the nervous system to parse out false cues from true environmental conditions. Previous work has reported that, even when it is possible to re-weight sensory input, shifting focus onto somatosensation and/or vestibular sense, older adults will still attempt to utilize what little (or inaccurate) visual input is available.[5,88] In general, the healthy young participants in this study were capable of overcoming this temptation and properly re-weight sensory input, as evidenced by insignificant differences between conditions 3+6 and 2+5.[86]

While no significant differences were found when simply comparing preference conditions 2+5 versus 3+6 in our healthy young participants, the relationship between these conditions, quantified as the preference ratio, did vary between the rambling and trembling components. The ML rambling SampEn preference ratio was calculated to be 0.95, while that of trembling was 1.08, a difference that is both statistically and physiologically significant. In this application, a preference ratio value over 1 represents greater SampEn (lower predictability) in visual conflict, as induced in conditions 3 and 6, compared to blacked-out vision in conditions 2 and 5. On the other hand, a preference ratio value less than 1 represents lower predictability in the absence of vision, compared to visual conflict. This outcome highlights the rambling trajectory's high degree of reliance on vision, even when incorrect, as evidenced by the lower entropy (higher predictability) in visual conflict conditions 3 and 6. The trembling trajectory, conversely, was more influenced by the absence of vision, decreasing entropy more drastically in the blacked-out visual conditions 2 and 5. The differing effects observed in rambling and trembling components allude to distinct compensatory postural control mechanisms that are used to overcome such sensory challenges.

While these findings capture healthy balance behaviors that accompany intact sensorineural function, they will gain even greater value in comparison to aging and pathological populations. In addition to amplifying observed effects on the trembling time series, we would expect that individuals with impaired sensory re-weighting capabilities, such as Parkinson's disease, would experience substantial changes to the rambling time series and to preference measures in particular.[68,89] Such differences would reflect the lowered efficiency of supraspinal control and neuromotor impairments typically observed in patients with Parkinson's disease.[81,89] On the other hand, in patients with sensation-specific deficits, like peripheral neuropathy or

vestibular loss, we would expect to simply exacerbate the already-limited availability of sensory input and introduce an even larger discrepancy between motor planning and output.

The ability to catalog trends in RM-TR measures during the SOT procedure would undoubtedly add richness to the test as a whole, differentiating an individual's balance deficit by its source. With this information, clinicians may be able to tailor interventions to efficiently target an individual's deficit, improving rehabilitation outcomes. However, studies that include both of these methodologies are extremely limited, especially in older, pathological populations. Therefore, it is recommended that future work pursue inclusion of individuals with a range of sensorineural capabilities to further add to our understanding of the role of sensation in balance and its rambling and trembling components.

Limitations

While there is certainly cause for confidence regarding the present results, it is important to note several limitations of our findings. First, this work was done with healthy young participants, a demographic that may not directly benefit from these advancements, nor best reflect behaviors of clinical populations that would. To maximize impact, it is imperative that future work documents these sway characteristics in clinical populations. Next, testing procedures, including trial length and order, were performed in accordance with the standardized Sensory Organization Test protocol. As such, testing conditions were completed in an identical, sequential order, potentially introducing task order bias to our results. Additionally, each condition was repeated in three 20-second trials. Although this trial duration is standard to the SOT protocol, 20 seconds is significantly shorter than many existing COP analyses that typically run for 60 seconds or greater, removing a degree of consistency with previous work and limiting generalizability of our outcome measures.[80,90] Therefore, to be able to relate investigations of rambling-trembling behavior during

SOT procedures, it is recommended that future studies extend trial duration to a minimum of 60 seconds.

4.5. Conclusions

This study provides compelling justification for the implementation of RM-TR methods in Sensory Organization Test analyses. In healthy individuals, sensory challenges induced changes to sway, primarily in the trembling component, reflecting impaired sensorimotor feedback but proficient supraspinal control. These findings provide a strong foundation with which we may build upon our understanding of postural control in both basic research and clinical applications. Such advancements would add substantial depth to our ability to assess, diagnose, and treat balance disorders in a targeted manner, ultimately preventing falls and improving overall quality of life with aging and disease.

Conflict of Interest Statement

None.

Tables and Figures

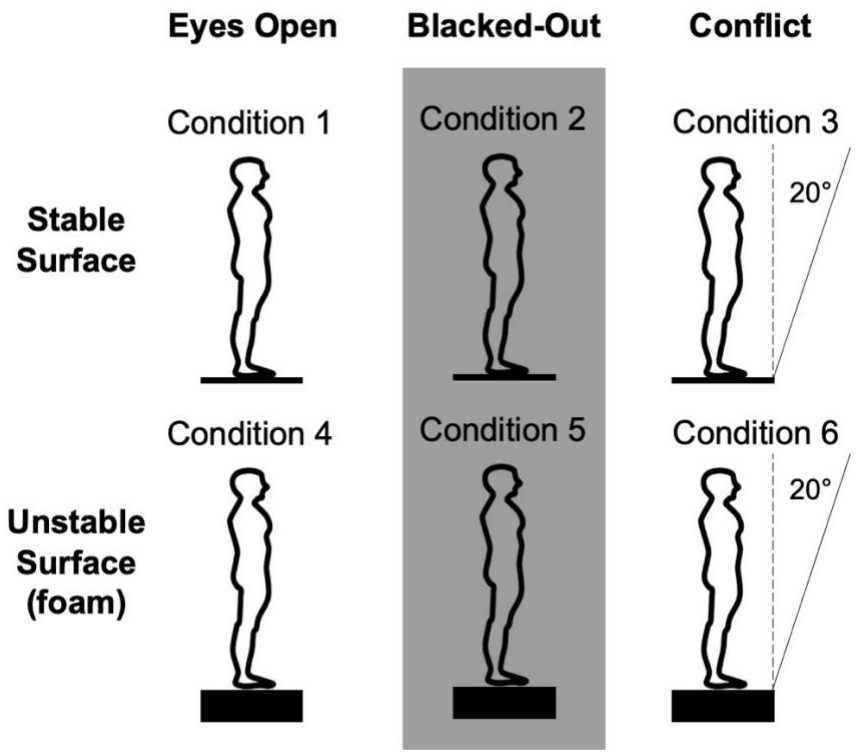

Figure 9. Six sensory conditions utilized in the VR-ComBAT Sensory Organization Test. Conditions 1-3 require the participant to stand directly on the flat, stable force plate, while conditions 3-6 introduce a piece of foam between the feet and force plate. Conditions 1 and 4 simulate eyes open visual motion, conditions 2 and 5 have vision blacked out, and conditions 3 and 6 rotate the visual field independent of sway, creating a sensory conflict. Adapted from Moon et al. (2021).[77]

Table 4. Primary sensory systems used in Sensory Organization Test conditions, as adapted from the Balance Manager Systems Clinical Interpretation Guide: Computerized Dynamic Posturography, NeuroCom International, Inc.[86]

Test Condition	Vision	Support Surface	Primary Sensory System
1	Eyes open	Firm	Somatosensory
2	Blacked-out	Firm	Somatosensory
3	Conflict	Firm	Somatosensory
4	Eyes open	Unstable	Visual
5	Blacked-out	Unstable	Vestibular
6	Conflict	Unstable	Vestibular

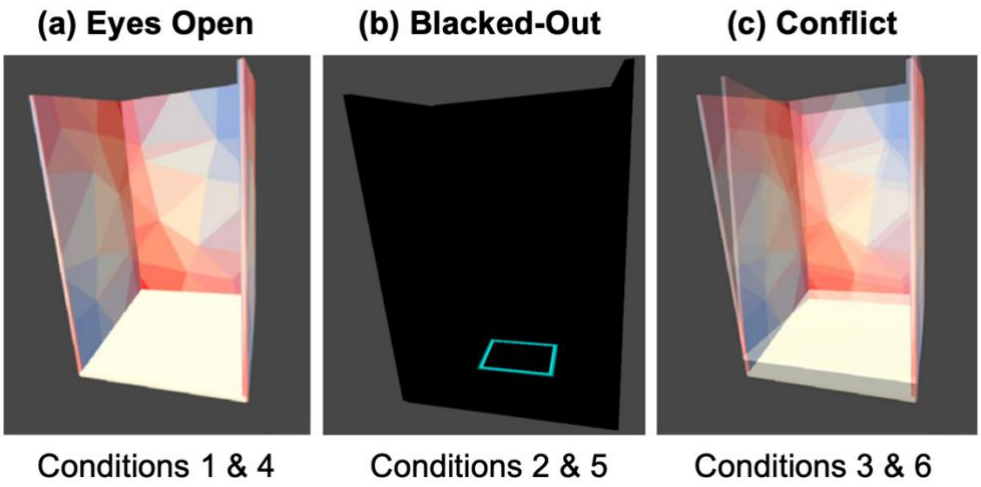

Figure 10. Virtual reality environments used to achieve eyes open, blacked-out, and conflict visual conditions, as required in the VR-ComBAT Sensory Organization Test. Adapted from Moon et al. (2021).[77]

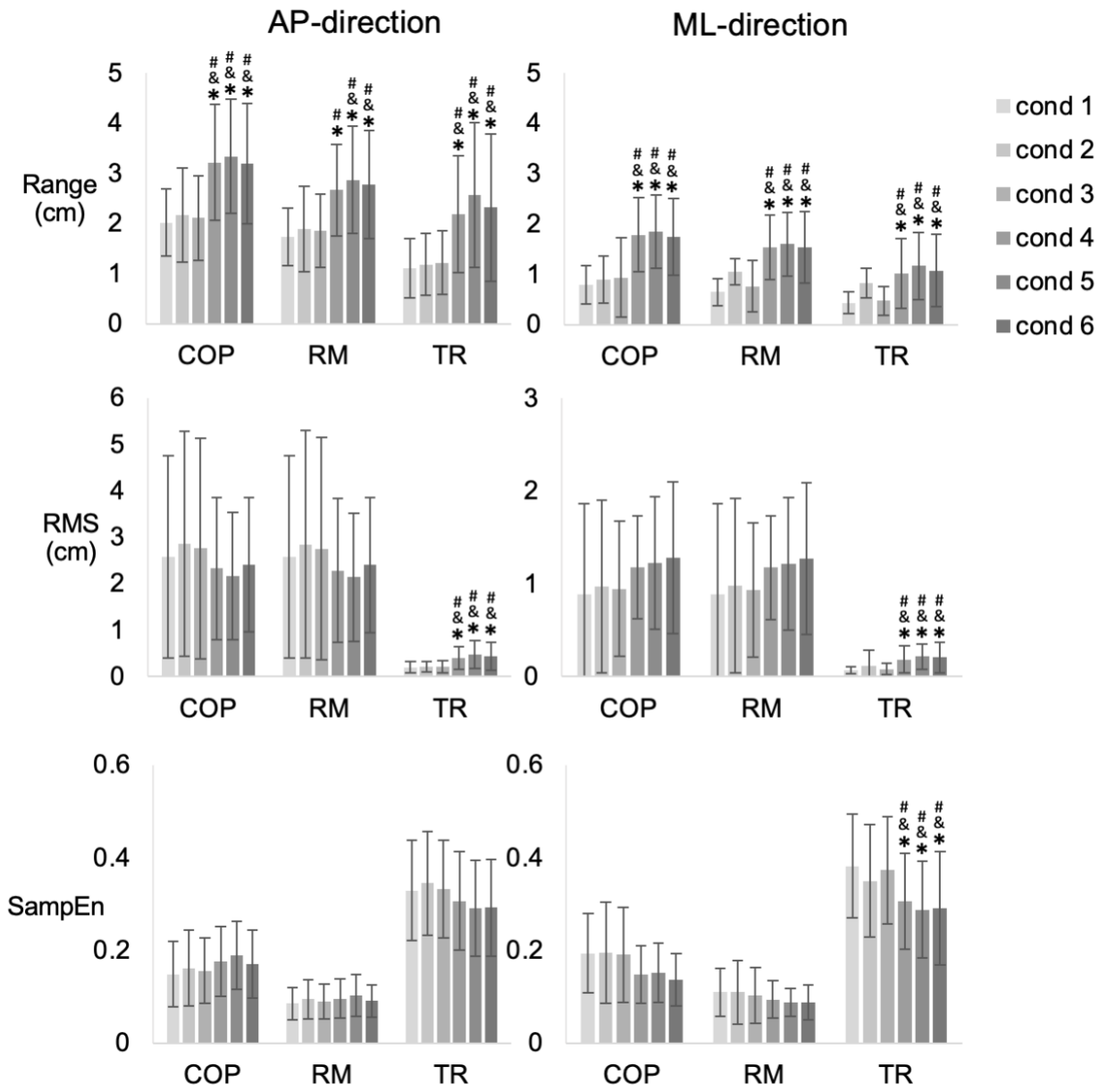

Figure 11. Mean outcome measures and standard deviations of COP, RM, and TR time series across all SOT conditions (cond 1-6). Significant differences (*p*<0.05*)* from cond 1, 2, and 3 are shown with an asterisk (*), an ampersand (&) and a hash (#), respectively.

Table 5. Changes in outcome measures based on sensory input. Significant differences (p<0.05) are bolded and italicized.

	ΔRange (cm)						**ΔRMS (cm)**						**ΔSampEn**					
	COP		**RM**		**TR**		**COP**		**RM**		**TR**		**COP**		**RM**		**TR**	
	AP	ML	AP	ML	AP	ML	AP	ML	AP	ML	AP	ML	AP	ML	AP	ML	AP	ML
Somatosensation (cond 2 vs 1)	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.3	0.1	0.3	0	0	0	0	0	0	0	0
Vision (cond 4 vs 1)	***1.2***	***1.0***	***0.6***	***0.6***	***0.9***	***0.7***	0.3	-0.3	0.3	-0.3	***0.1***	***0.2***	0	0	0	0	0	***-0.1***
Vestibular (cond 5 vs 1)	***1.3***	***1.1***	***0.6***	***0.6***	***1.2***	***0.7***	0.3	-0.4	0.3	-0.5	***0.2***	***0.2***	0	0	0	0	0	***-0.1***
Preference (cond 3+6 vs 2+5)	0	0	0	0	0	0	0	-0.1	0	-0.1	0	0	0	0.1	0	0	0.1	0.1

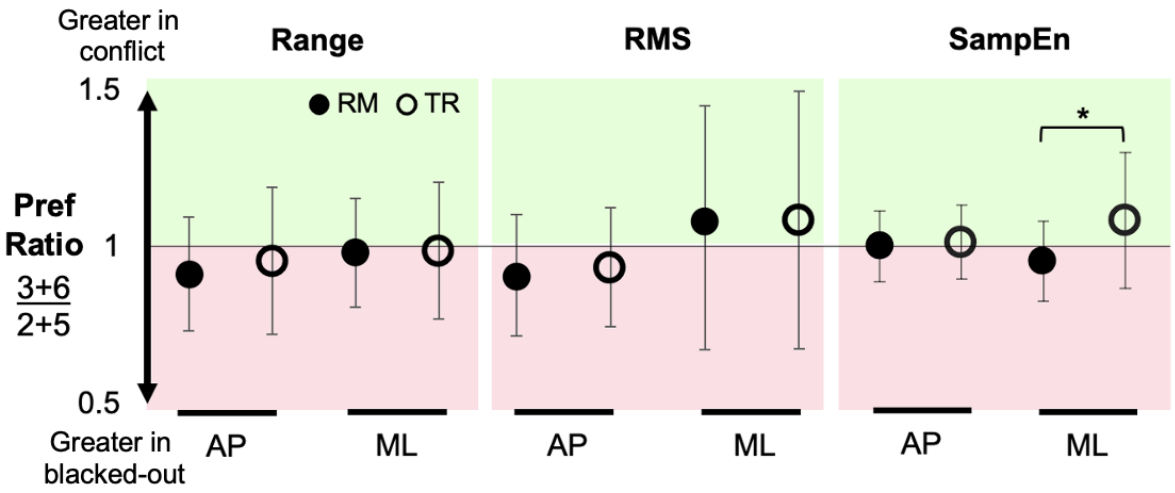

Figure 12. Preference (pref) ratios for each outcome measure, describing the relative relationship between conflict and blacked-out visual conditions. Significant differences (p<0.05) between RM and TR components are indicated with an asterisk (*).

Chapter 5: Subthreshold white noise vibration alters trembling sway in older adults

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Declarations of Interest: none

Highlights:

- Subthreshold vibration increases sway range, variability, and predictability
- Peripheral/spinal (trembling) mechanisms were influenced by subthreshold plantar vibration
- Effects of vibration may be dependent on location, duration, and magnitude

Abstract

Background: Somatosensory deficit is a significant contributor to falls in older adults. Stochastic resonance has shown promise in recent studies of somatosensation-based balance disorders, improving many measures of stability both inside and outside of the clinic. However, our understanding of this effect from a physiological perspective is poorly understood. Therefore, the primary goal of this study is to explore the influence of subthreshold vibratory stimulation on sway under the rambling-trembling framework.

Methods: 10 Healthy older adults (60-65 years) volunteered to participate in this study. Each participant underwent two randomized testing sessions on separate days, one experimental and one placebo. During each session, the participants' baseline sway was captured during one 90-second quiet standing trial. Their sensation threshold was then captured using a custom vibratory mat and 4-2-1 vibration perception threshold test. Finally, participants completed another 90-second quiet standing trial while the vibratory mat vibrated at 90% of their measured threshold (if experimental) or with the mat off (if placebo). While they completed these trials, an AMTI force plate collected force and moment data in the anteroposterior (AP) and mediolateral (ML), from which the center of pressure (COP), rambling (RM), and trembling (TR) time series were calculated. From each of these time series, range, variability (root-mean-square), and predictability (sample entropy) were extracted. One-tailed paired t-tests were used to compare baseline and during-vibration measures.

Results: No significant differences were found during the placebo session. For the experimental session, significant increases were found in AP TR range, ML TR RMS, AP COP predictability, and AP & ML TR predictability. The TR time series was particularly sensitive to vibration, suggesting a strong influence on peripheral/spinal mechanisms of postural control.

Significance: Though it is unclear whether observed effects are indicative of "improvements" or not, it does suggest that there was a measurable effect of subthreshold vibration on sway. This knowledge should be utilized in future studies of stochastic resonance, potentially acting as a mode of customization, tailoring vibration location, duration, magnitude, and frequency content to achieve the desired effect. One day, this work may aid in our ability to treat somatosensation-based balance deficits, ultimately reducing the incidence and severity of falls in older adults.

Keywords: Stochastic resonance; balance; rambling-trembling; postural control; sensation; aging

5.1. Introduction

As the leading cause of injury among individuals aged 65 and older, accidental falls present a substantial and ongoing threat to older adults.[51] Healthy aging introduces a myriad of physiological changes that limit the body's ability to assess its position in space and respond to perturbations. Among these changes is an increased sensory threshold, in which a progressively greater magnitude of stimuli is required to achieve sensation.[5,6,91,92] This dampening of the senses is a significant contributor to falls in older adults, limiting the reliability of somatosensory input required to maintain balance.

Somatosensory decline, as seen in healthy aging, is thought to decrease physiologic complexity, a vital attribute of robust, stable balance.[69,93,94] Decreasing sway complexity can result in behavior that is either too random or too repetitive, both of which are associated with increased fall risk in older adults and those with balance disorders, such as Parkinson's Disease.[95] In quiet standing, age-related declines in complexity often manifest as increased magnitude, variability, and predictability of the center-of-pressure.[96–98] Such behavior is indicative of sway that is exceedingly repetitive, largely unstable, and presents a high degree of fall risk.

Treatment options for those suffering from somatosensory loss are extremely limited, but stochastic facilitation has the potential to recover this loss in sensation and subsequent complexity. The phenomenon of stochastic resonance has been observed in a wide variety of populations, from children with cerebral palsy to older adults and those with diabetic peripheral neuropathy, using noise to enhance pre-existing tactile signals in the environment.[97,99–101] This effect is noted as a phenomenon because the exact mechanism has yet to be fully explained, but researchers suggest that this effect is achieved through the augmentation of environmental stimuli, boosting existing signals to levels perceivable by individuals with heightened sensory thresholds.[96,99]

However, this proposed effect is not well documented, especially within the rambling-trembling framework, an analytical method that decomposes the center of pressure into large-scale movement of an equilibrium point and oscillations around this point.[45,92,102–104] Thus, the primary goal of this study is to assess the influence of vibrotactile stochastic facilitation on the improvement of physiologic complexity in the aging population. Additionally, although the proposed mechanism of stochastic facilitation aligns with its observed effects, the exact mechanism is not fully understood.[105–107] Therefore, the secondary goal of this study is to provide insight into the mechanism of action of vibrotactile-based stochastic facilitation with respect to the individual contributions of rambling and trembling components of the center of pressure. Based on these goals, it was hypothesized that (1) subthreshold vibration will decrease system (1.a) magnitude, (1.b) variability, and (1.c) predictability (increase SampEn), and (2) the TR time series will show more prominent changes to sway compared to COP and RM time series, demonstrated by the number of significant differences.

5.2. Material and Methods

5.2.1 Participants

Ten healthy older adults (aged 62.8 ± 1.6 years, 7 female) volunteered to participate in this study. All participants were informed of the study risks and benefits and provided written consent, as approved by the University of Kansas Institutional Review Board. Participants with a history of neurological disorder, balance impairment, and/or significant injury to the trunk or lower limbs were excluded from the study.

5.2.2 Vibratory Mat

The tests conducted in this study required subjects to stand on a custom-made vibrating mat. This mat was composed primarily of Shore A50 silicone, with three embedded eccentric rotating mass motors (307-103, Precision Microdrives, London, UK) beneath each foot, positioned approximately at the heel, the first metatarsal, and the fifth metatarsal. The mat measures 0.5m x 0.4m x 13mm. The motors were placed using a standardized stance width (17cm) and angle (14° between the feet).[63] The motors are powered by a 5-volt and 12-volt external power supply. They are controlled with DRV2605 chips (Texas Instruments, Dallas, TX, USA) and custom-built Arduino (Arduino, Somerville, MA, USA) code. The motors output white noise vibration, as validated in previous work.[108] The mat was placed atop a 6-axis AMTI force plate (Watertown, MA, USA).

5.2.3 Testing Conditions

Participants completed two testing sessions (stimulation and placebo) in a randomized order on separate days. Testing sessions were structured identically and had three primary tests: (1) baseline sway, (2) sensation threshold determination, and (3) stimulation sway, as shown in Figure 14. The baseline sway trial was performed prior to exposure to vibratory stimuli of any kind. Participants stood quietly, barefoot, on the vibratory mat (with motors off) for 90 seconds with eyes closed and feet aligned to the standardized stance width and angle. To determine the sensory threshold, subjects then stood on the mat and completed a modified 4-2-1 vibration perception threshold (VPT) test developed by Whorley and colleagues (2020), which calculates the individual's threshold as a percentage of the maximum motor output magnitude.[109,110] Finally, participants stood quietly with eyes closed on the mat for 90 seconds; for the stimulation session, the motors administered subthreshold white noise vibration at 90% of their measured threshold.[111] During the

placebo session, participants still stood on the mat for 90 seconds, but received no stimulation. The session order was randomized and participants were blinded to which session included vibration.

5.2.4 Data Collection and Analysis

Foot-floor kinetic data were collected at 100 Hz using the 6-axis AMTI force plate underneath the vibratory mat and a 16-bit A/D acquisition system (Cambridge Electronic Design, Cambridge, UK). Using MATLAB software (Mathworks, Natick, MA, USA), data were filtered with a 4th order 10 Hz low-pass Butterworth filter and down-sampled to 50 Hz. Spectral analysis of frequency content was used to ensure force artifact from motor vibration was filtered out prior to analysis. This data were then used to calculate the COP time series.[36] Force and COP time series were then used to calculate RM and TR time series in the AP and ML directions.[45] From these time series, range, root-mean-square (RMS) and sample entropy (SampEn) were extracted. SampEn input parameters of m = 2 and r = 0.1 were selected based on recommendations from Nichols (2020).[64]

5.2.5 Statistical Analysis

Microsoft Excel was used to perform statistical analyses. Descriptive statistics and Jarque-Bera tests were used to evaluate normality of the data distribution. One-tailed, paired *t* tests were performed to compare differences in sway outcome measures (range, RMS, and SampEn) between baseline and stimulation/placebo sway trials. Significance was set to $p < 0.05$. A statistical power analysis was used to determine minimum sample size for this study. With alpha = 0.05 and power = 80%, the required sample size was estimated to be N=10 participants.

5.3. Results

With a large effect size (d = 0.92) and final sample size of 10, post hoc statistical power was calculated to be 81%. The average measured sensation threshold was 45.1 ± 11.0% of the maximum motor power, which corresponds to approximately 2.5 Newtons of vibrational force.[108] No significant differences were found between baseline and placebo trials. Representative stabilogram plots for COP, RM, and TR components during baseline and stimulation trials are shown in Figure 15. Differences between baseline and stimulation trials are detailed below.

5.3.1 Range

Mean range in the anteroposterior (AP) and mediolateral (ML) directions increased in stimulation sway compared to baseline for the COP, RM, and TR time series, with a significant increase (p = 0.039) in AP TR range (Figure 16a-b, Table 6). AP TR range increased between baseline and stimulation trials for 7 out of 10 total participants (Figure 16).

5.3.2 Root-Mean-Square (RMS)

RMS values were comparable in the baseline and stimulation trials in the AP-direction, with no significant differences between trials for COP, RM, or TR (Figure 16c). In the ML-direction, mean RMS decreased for the COP and RM time series, but not significantly (Figure 16d). For the TR time series, ML RMS increased from the baseline sway trial to stimulation (p = 0.024). For this measure, 7 out of 10 subjects experienced an increase in TR ML RMS (Figure 16).

5.3.3 Sample Entropy (SampEn)

COP AP SampEn showed a significant decrease (p = 0.045) between baseline and stimulation trials (Figure 16e), but individual differences varied, with 5 subjects increasing and 5 decreasing (Figure 17). RM showed no significant differences between baseline and stimulation sway SampEn in the AP- or ML-directions. TR showed a significant decrease in SampEn between

baseline and stimulation in the AP- (p = 0.009) and ML-direction (p = 0.038). This decreasing trend in TR SampEn was present in 8 out of 10 and 9 out of 10 total subjects in the AP- and ML-directions, respectively (Figure 17).

5.4. Discussion

The primary aim of this study was to explore the effects of subthreshold vibratory stimulation on the center of pressure (COP) and its rambling (RM) and trembling (TR) components. The placebo trials yielded no significant differences to baseline in any sway measure, reinforcing the relationship between observed effects and vibratory stimulation.

There were two main hypotheses in this study: (1) subthreshold vibration will decrease system (1.a) magnitude, (1.b) variability, and (1.c) predictability (increase SampEn) and (2) the TR time series will show more prominent changes to sway compared to COP and RM time series, demonstrated by the number of significant differences.

Sway magnitude is known to increase in aging, covering a larger range of position in both the AP- and ML-direction.[68,98,112] Contrary to hypothesis 1.a, range increased between baseline and stimulation trials, suggesting that subthreshold white noise vibration was counterproductive to reversing this effect of aging. Sway variability (RMS) also tends to increase in aging.[68,112] There were no significant differences in RMS between baseline and stimulation in the AP-direction, with near-identical trial means. In the ML-direction, there was a significant increase in TR RMS from baseline to stimulation, despite COP and RM means trending downward (albeit insignificantly). The decreasing trend observed in COP and RM loosely supports hypothesis 1.b, but the significant increase in TR does not align with this conclusion. Results of this study do not support hypothesis 1.c, which stated that vibratory stimulation would decrease predictability, exhibited by significant

decreases in SampEn (increases in predictability) from baseline to stimulation for AP COP and AP and ML TR.

Stochastic facilitation has been shown beneficial in studies with older adults[92,113], individuals with diabetic peripheral neuropathy[101,114], stroke survivors[115,116], and athletes.[117] These benefits have been demonstrated in a multitude of experimental methods, including center-of-pressure and gait analyses, plantar pressure distribution, clinical evaluations of spasticity and range of motion, agility tasks, and direct assessment of sensation threshold.[99,118–120] Despite this promise, findings of this study do not directly support the previously-reported benefits of stochastic facilitation.

However, these conflicting results are more likely a reflection of the immense variability in methods between studies, rather than a cause for concern regarding the efficacy of stochastic facilitation. The present study utilized a custom vibratory mat and modified 4-2-1 VPT protocol to establish the individual's subthreshold vibration magnitude, inspired by previous work, with 6 motors embedded at the approximate location of three major bony landmarks in each foot.[109,110,121,122] But vibration has been applied in many different ways that have undoubtedly contributed to discrepancies in the observed effects between studies. It is possible that varying conditions, such as stimulation location, duration, magnitude, and frequency content of vibration, induce unique sway responses.

Additionally, our results further elucidate inconsistencies in the literature regarding observed trends in nonlinear COP analysis in aging. In this study, it was hypothesized that vibration would decrease predictability (increase SampEn). Though not tested directly, it was assumed that older individuals tend to have lower motion complexity, and therefore predictability. This assumption was based on Lipsitz & Goldberger's Loss of Complexity Hypothesis, which

states that a loss of physiological complexity contributes to many negative characteristic effects of aging, making these systems less robust and adaptable.[123] Since the emergence of nonlinear methodology, researchers have attempted to quantify this complexity through measures such as sample, approximate, and multiscale entropy, stating that an increase in predictability (or regularity) indicates lower complexity. However, predictability and complexity are not synonymous, and thus observed effects of aging and disease, with respect to entropy, are inconsistent across studies.[94,124] For example, Duarte & Sternad (2008) and Degani et al (2017) report higher entropy values in older adults compared to healthy young adults, indicating a positive change in our reported results. At the same time, Costa et al. (2007), Manor & Lipsitz (2013), and Roerdink et al. (2006) find lower entropy values, compared to healthy counterparts, in older adults, those experiencing visual and/or somatosensory impairment (like that seen in older adults), and individuals recovering from stroke, respectively.[43,69,97]

Findings from this study simultaneously highlight the potential benefits and underscore the current limitations of both stochastic facilitation and the nonlinear methods used to assess its efficacy. Subthreshold white noise vibration showed seemingly counterproductive effects on sway range, variability, and predictability, but it is unclear whether this is due to vibration settings, assumptions about aging, or true negative consequences of the vibration. It is also uncertain whether existing assumptions about changes in outcome measures that typically signify balance "health" (i.e. decreasing range and RMS or increasing SampEn) are truly indicative of positive change when considering independent RM and TR components.[68,125]

It is also important to note that, although participants in this study were considered older (aged 60-65 years), it is possible that they were too young to experience many substantial age-related somatosensory declines, more closely resembling their younger counterparts rather than

someone in their 70's or 80's. Measured vibration perception thresholds for this 60-65 year old group (45% motor power, ~2.5N force) were considerably higher than previously measured thresholds for healthy young adults, aged 18-34 years (24% motor power, ~1N force), but it is predicted that the sensory degradation that occurs beyond 65 years would impose even greater increases in threshold and amplify (or otherwise alter) observed sway effects.[108,109] Indicators of balance health improvement from stochastic facilitation are largely dependent on the initial state, as a product of aging and/or pathology.[95,116,126] Therefore, it is imperative that future work samples from populations of older individuals (65+) and specifically those experiencing somatosensory-linked balance disorders, such as diabetic peripheral neuropathy, to fully understand the effects of such an intervention on the people that may benefit the most.

The second hypothesis, which stated that the TR time series would show the most prominent changes with vibration, is supported, as demonstrated by the number of significant differences between baseline and stimulation trials. Of the six measures utilized in this study (range, RMS, and SampEn in the AP and ML directions), four were found to be significantly different from their respective baseline TR values. Meanwhile, the COP time series found only one significant difference (AP SampEn) and the RM time series identified none. The implications of this finding are especially intriguing when considering the hypothesized physiological link between postural control and these rambling and trembling components of sway.

Zatsiorsky and Duarte developed rambling-trembling decomposition as a method of distinguishing two contributions to sway: large-scale movement of an equilibrium point and oscillations around that point.[45] Some researchers have taken this concept several steps further and propose that rambling and trembling components of the COP represent centrally (supraspinal) and peripherally (spinal) controlled movement, respectively.[11,12,48,50] Under this framework, our

findings suggest that stochastic facilitation may most directly impact oscillatory motion and peripheral control mechanisms of postural control, leaving the ability to establish (and adjust) the equilibrium point relatively unaffected.

Though the measured effects of vibration in this work could be endlessly debated as "good" or "bad," one conclusion can be agreed upon: there was in fact an effect. Subthreshold white noise vibration produced a sharp contrast between COP, rambling, and trembling components, with trembling sway (and its proposed underlying peripheral drivers) showing the most prominent changes with stochastic facilitation. Consequently, this type of intervention may be most beneficial applied on a case-by-case basis, tuning attributes such as vibration location, duration, magnitude, and frequency content to achieve the desired effect; suprathreshold (above-threshold, perceivable) vibration, for example, may more directly target the rambling component as opposed to trembling. Of course, further work must be done to understand the differing influence of these factors before developing such a targeted approach.

5.5. Conclusions

These results demonstrate the ability of vibration-based stochastic facilitation to induce quantifiable changes to postural sway. Although there remains much to learn with regard to the interpretation and optimization of this effect, subthreshold white noise vibration elicited measurable differences to the trembling component of the center of pressure, modulating the magnitude, variability, and predictability of oscillatory sway motion. Findings from this study may be used to inform future work that seeks to implement stochastic facilitation in older adults and those with clinical balance deficits. Ultimately, this work may aid in the reduction of fall-related

injuries and deaths, maintenance of physical mobility and improvement of overall quality of life in aging.

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Tables and Figures

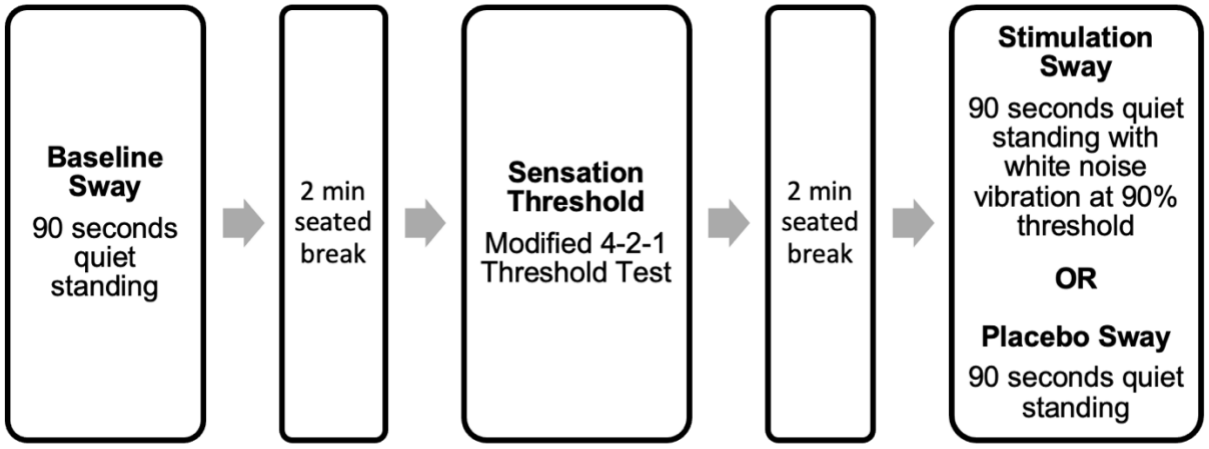

Figure 14. Protocol flow for each testing session, including (1) baseline sway, (2) sensation threshold determination, and (3) stimulation (or placebo) sway with 2-minute seated breaks between trials.

Table 6. Mean and standard deviation (SD) of outcome measures for baseline (BL) and stimulation (STIM) sway trials. Significant BL-STIM differences ($p<0.05$) are bolded and italicized.

Outcome Measure	Time Series	BL (mean ± SD)	STIM (mean ± SD)	*p*-value
AP Range (cm)	COP	2.384 ±0.670	2.769 ±0.828	0.086
	RM	1.691 ±0.429	1.972 ±0.653	0.131
	TR	1.157 ±0.315	1.358 ±0.443	***0.039***
ML Range (cm)	COP	1.243 ±0.268	1.356 ±0.399	0.261
	RM	0.962 ±0.259	0.985 ±0.264	0.433
	TR	0.601 ±0.180	0.748 ±0.292	0.089
AP RMS (cm)	COP	0.153 ±0.108	0.151 ±0.120	0.471
	RM	0.150 ±0.110	0.149 ±0.122	0.479
	TR	0.016 ±0.006	0.017 ±0.005	0.196
ML RMS (cm)	COP	0.358 ±0.085	0.337 ±0.114	0.083
	RM	0.358 ±0.085	0.337 ±0.114	0.083
	TR	0.007 ±0.002	0.008 ±0.003	***0.012***
AP SampEn	COP	0.217 ±0.091	0.182 ±0.182	***0.045***
	RM	0.058 ±0.012	0.052 ±0.052	0.194
	TR	0.446 ±0.070	0.382 ±0.382	***0.005***
ML SampEn	COP	0.122 ±0.042	0.109 ±0.109	0.176
	RM	0.045 ±0.012	0.045 ±0.045	0.476
	TR	0.268 ±0.060	0.235 ±0.235	***0.019***

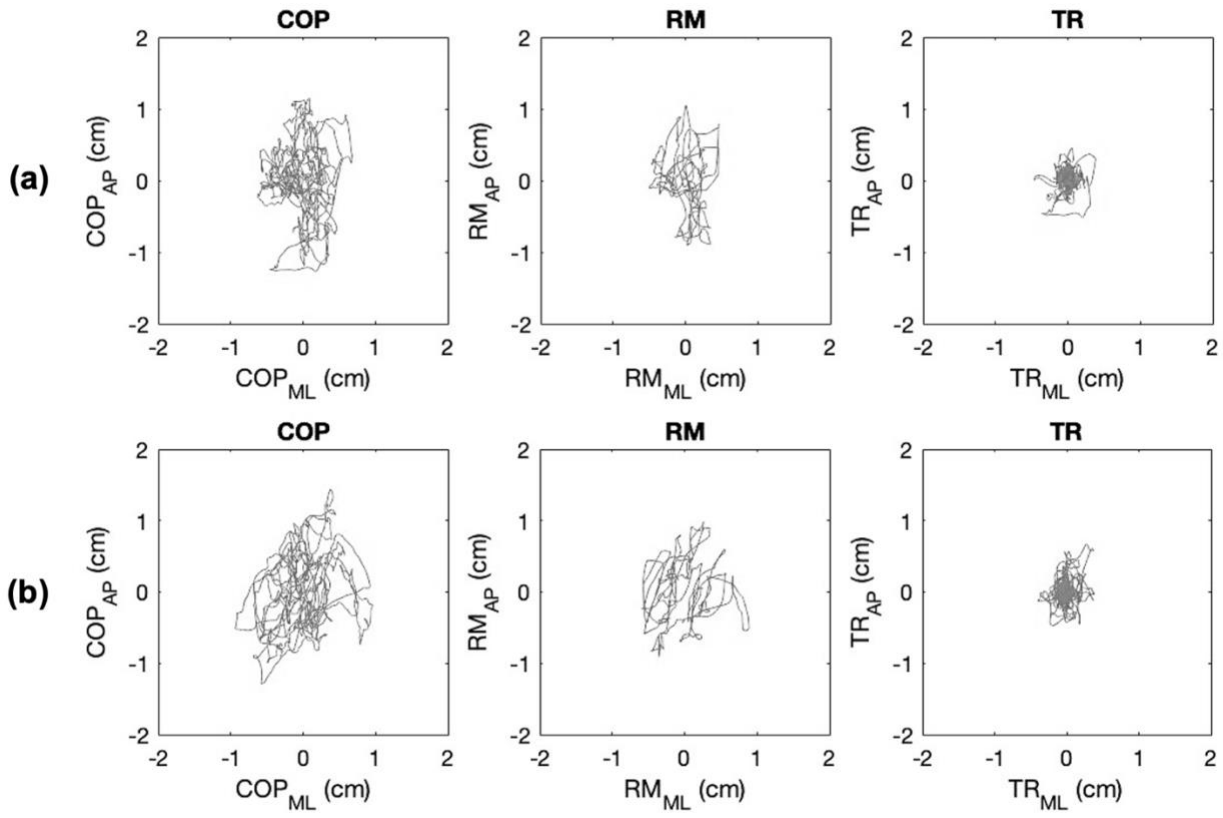

Figure 15. Representative stabilogram plots for an individual subject, including rambling (RM) and trembling (TR) components for 90-second (a) baseline and (b) stimulation trials.

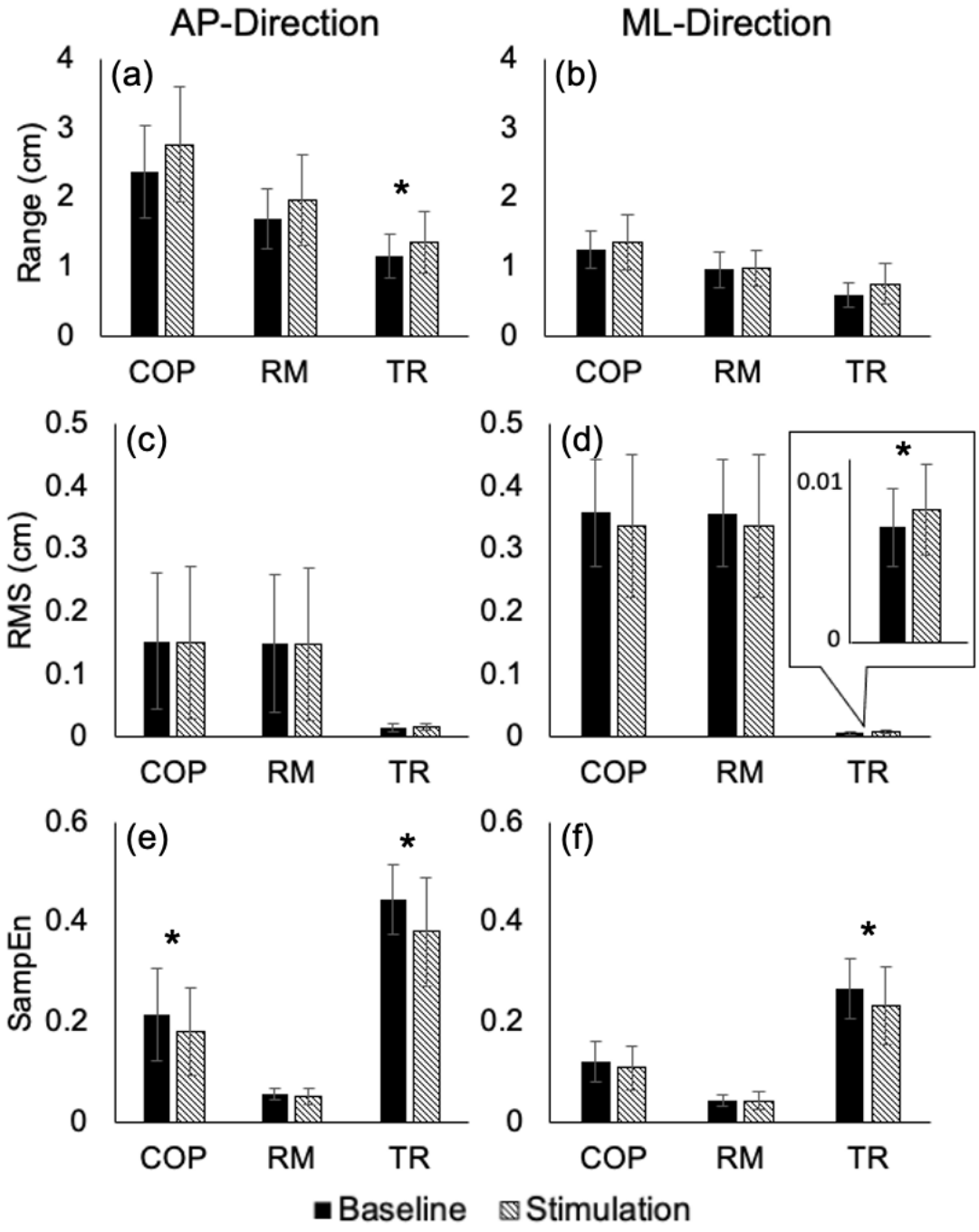

Figure 16. Mean outcome measures for baseline and stimulation sway trials. Standard deviations are shown with error bars. Significant baseline-stimulation differences (p<0.05) are shown with asterisks (*).

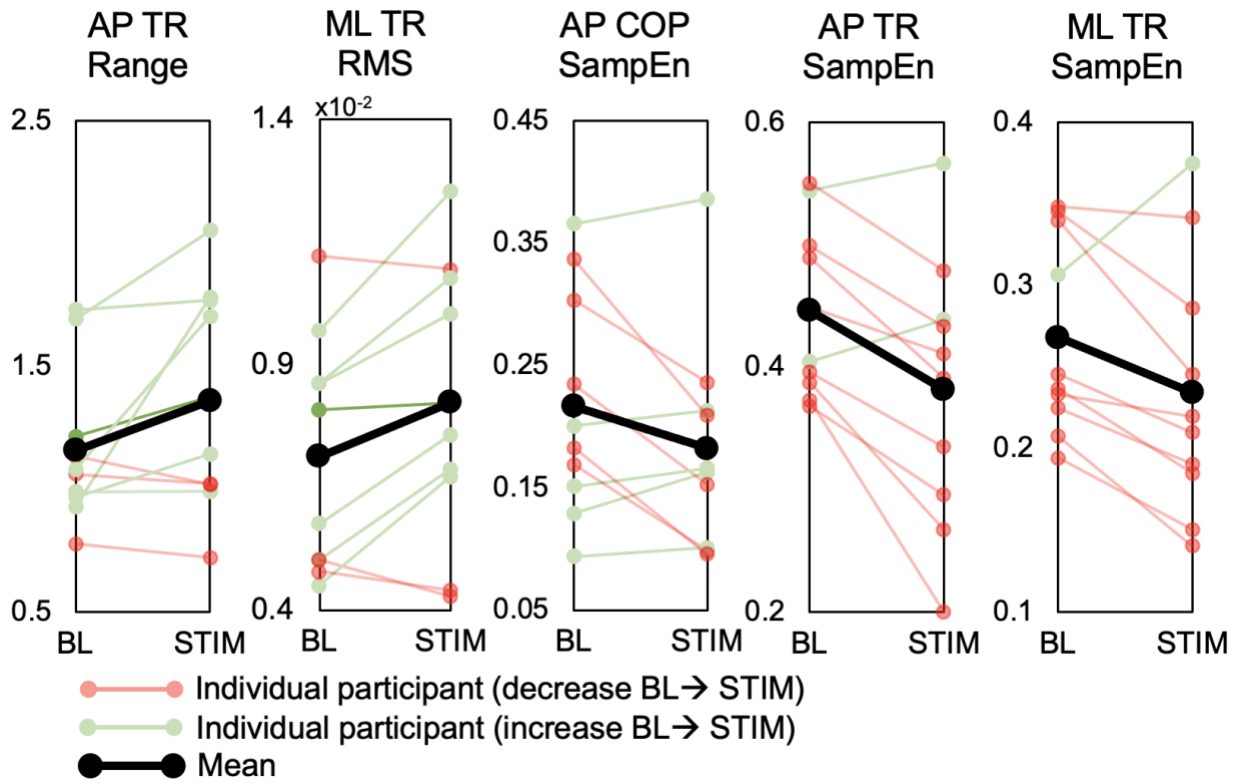

Figure 17. Baseline (BL) and stimulation (STIM) trial values for individual participants in selected outcome measures. Measures selected include only those found to have a significant difference between BL and STIM trials, as determined by paired t-tests.

Chapter 6: Summary

Postural stability is nothing short of a miraculous feat. The ability to maintain upright stance requires constant monitoring of internal and external conditions such that the body may accurately set (and reset) a stable equilibrium point using fine muscular contractions. To assess the body's position, both in space and relative to itself, it must gather sensory input from the visual, somatosensory, and vestibular systems. Together, these senses provide the basis by which the body may work to counteract environmental and gravitational forces and remain upright.

The body is incredibly robust to challenges that influence this complex sensorimotor feedback system, but may nonetheless be impacted by conditions such as stroke, Parkinson's disease, and aging, that ultimately decrease stability and increase the overall risk of falls. The sensory systems become particularly vulnerable to damage, limiting the availability of this vital input and diminishing the accuracy and precision of the overall system.

The work outlined in this dissertation sought to explain the mechanisms by which postural stability is maintained through the lens of sensory feedback and neuromotor control. This was accomplished primarily through the implementation of rambling-trembling analytical techniques to center of pressure sway. The addition of this methodology enhances traditional center of pressure interpretation by parsing out individual trajectories by the control systems that dictate them. Rambling is defined as motion of the equilibrium (or reference) point, while trembling is composed of oscillations around this point.[45] These trajectories are thought to be supraspinal (central) and spinal (peripheral) in origin, respectively.[80]

Existing rambling-trembling studies have revealed distinct behvaiors of these trajectories based on the health of the postural control system, as determined by conditions such as athletic expertise, external sensory challenges, and disease state.[60,68,81,127,128] Such specificity could add

substantial value to clinical postural sway analyses, elucidating the underlying the cause of an individual's balance deficit and enhancing our ability to administer targeted rehabilitation strategies. The more detail we can provide the clinician, the better and more efficiently they may treat their patients.

It it through this framework that the three specific aims of this dissertation were crafted. The first specific aim sought to catalog the effects of progressive somatosensory loss, using incrementally increasing thicknesses of foam to simulate the natural decline in plantar sensitivity that occurs in aging. Sway range, variability, and predictability increased with simulated deficit severity, with the most prominent changes occurring in the trembling time series. Unlike the center of pressure and rambling time series, the trembling trajectory showed consistent, quasi-linear changes with foam thickness, suggesting a strong link between this measure and availability of somatosensory input. Such observation could improve sensitivity of fall risk assessment, but the use of foam limits its implications in older adults. Future work should seek to replicate this finding in an older and pathological populations without the use of foam-based simulation, to ensure and expand generalizability.

The second specific aim took a deeper dive into the individual contributions and integration of the senses in healthy adults, utilizing a common clinical tool, the Sensory Organization Test. The test uses six sensory conditions with varying support surfaces and visual environments to isolate the individual contributions of somatosensation, vision, and vestibular sense, as well as characterize the sensory re-weighting that occurs during visual conflict. From this, we found that both vision and vestibular sense played a key role in the modulation of sway, especially in the trembling component. Across sensory conditions, sway range, variability, and predictability increased, with the majority of significant differences between conditions occurring in the

trembling outcome measures. The healthy participants were able to properly re-weight sensory input in the presence of a visual conflict, but rambling and trembling trajectories underwent distinct adaptations to do so. While trembling sway predictability was greater in the absence of vision, that of rambling was greater in visual conflict, a difference that is significant, both statistically and physiologically. Given the proposed drivers of rambling and trembling components, these findings suggest that spinal contributions to sway were more directly impacted by a lack of sensory input, whereas supraspinal contributions were most influenced by faulty (conflicting) cues. While these findings elucidate sensory-based postural control mechanisms of healthy individuals, further advancements will be made when we are able to compare them with those of sensory-impaired populations.

Lastly, the third specific aim documented the influence of stochastic facilitation, a potential intervention for somatosensory deficit, on sway in older adults. Effects of subthreshold vibration were somewhat unexpected, increasing range, variability, and predictability of sway. Under commonly accepted aging paradigms, including as the Loss of Complexity hypothesis, the present findings would suggest that stochastic facilitation had counterproductive rehabilitative effects on balance.[123] Though this conclusion may raise concern regarding the efficacy of stochastic facilitation interventions, it is important to note that trends associated with balance health have yet to be fully characterized and it is unclear whether existing assumptions are upheld under the rambling-trembling framework. The ambiguity of "health" in this application limits the interpretation of our findings, but it can be concluded that subthreshold vibration induced quantifiable changes to sway and its rambling and trembling components.

Though there remain many unanswered questions regarding the role of sensation in postural control, these three specific aims may contribute substantially to our ability to diagnose

and treat balance disorders. In combination with Gerber et al. (2022), specific aim 1 catalogued the progression of a simulated somatosensory deficit, providing greater depth to our understanding of gradual, sensation-based balance decline. Specific aim 2 isolated the influence of the three primary senses, somatosensation, vision, and vestibular sense, with respect to their role in postural control. And finally, specific aim 3 explored the potential therapeutic benefits of subthreshold vibration in the augmentation of environmental signals. Together, these findings have contributed to our overall comprehension of postural control and may one day be used to improve the sensitivity of fall risk assessment and efficacy of rehabilitative treatment strategies. This work is one small but meaningful step toward the ultimate goal of preventing falls, maintaining quality of life, and empowering our loved ones, against all odds, to continue to defy gravity.

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Appendix A: Stochastic Facilitation Mechanism

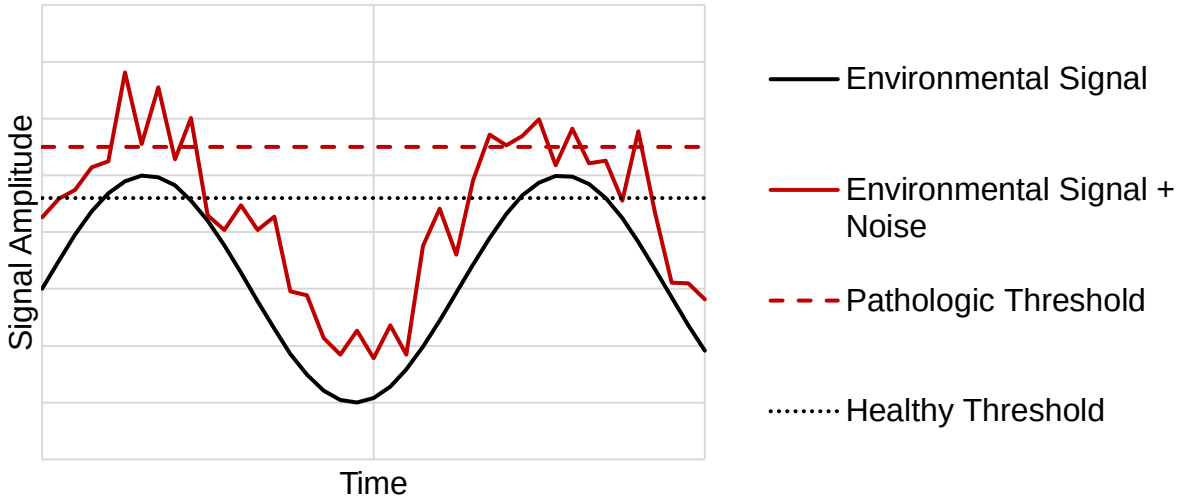

Figure A.1. Theorized mechanism of stochastic facilitation.[107] Environmental signals are represented by the black sine wave. A healthy individual's sensory threshold is symbolized by the dotted black line, with the environmental signal easily exceeding the minimal signal amplitude required for sensation. A pathologic (elderly, neuropathic, etc.) sensory threshold is represented by the dashed red line, which is substantially higher than the healthy counterpart, not allowing for sensation of the signal. The addition of noise to the environmental signal, shown by the solid red line, however, surpasses this heightened, pathologic threshold.

Appendix B: Custom Vibratory Mat

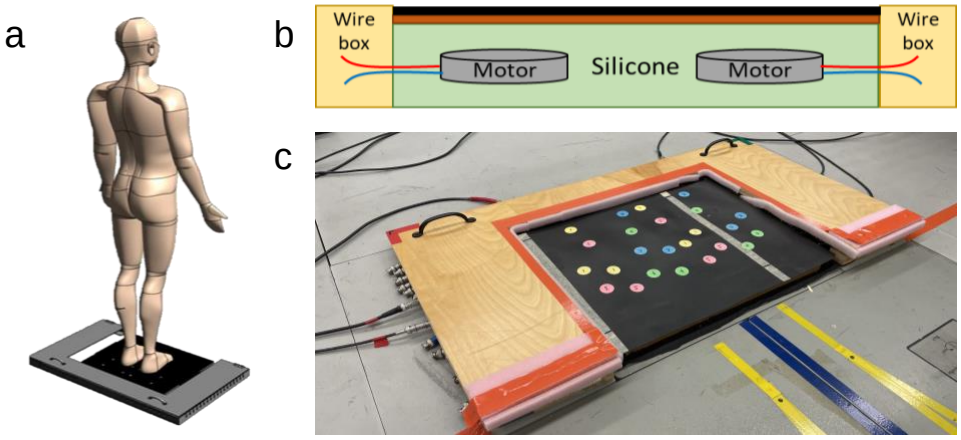

Figure A.2. Vibrotactile mat designed, built, and tested in the Biodynamics Research Lab, including (a) a computer-generated image of the mat in use, (b) layering of materials, wiring, and motors within the mat, and (c) the final mat prototype.

Appendix C: SA1 Experimental Protocol Documents

Informed Consent

Adult Informed Consent Statement

"Quiet Standing Analysis during Somatosensory and Visual Deficiencies"

INTRODUCTION

The Biodynamics Research Laboratory at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and not participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY

The purpose of this project is to collect quiet standing data on healthy adults under different levels of somatosensory feedback deficiency (standing on various thickness of foam) with either eyes open or closed. This data will be used to develop new measurement and analysis techniques used to detect somatosensory deficits patients with various pathologies. It is expected that the results from this study will help us to better understand the contribution of the somatosensory feedback in quiet standing, and how the body maintains its balance under a somatosensory deficiency. In the future, we hope to investigate the application or our new measurement and analysis techniques on patient populations (e.g. diabetes, stroke, Parkinson's disease) to determine how well they work to detect somatosensory deficits. Our long-term goal is to improve the physician's tool for detecting somatosensory deficits, so that an intervention can be introduced which would reduce the risk of the patient experiencing a fall.

In this project, movement, force, and electromyography (EMG - muscle and heart activity) data will be collected from healthy adults while each stand quietly on foam of different thicknesses. All tests are non-invasive and considered to be low-risk to the participant. The testing will provide the investigators with information about the how the participant's motor control system controls balance while standing on foam.

PROCEDURES

For this study, we will look at your quiet standing balance. First, you will be asked to change into your personal attire (shorts and t-shirt) that will allow us to easily place the sensors on your skin in the correct location. Next, we will record the following demographic and physical information:

- Name
- Gender
- Height
- Weight
- Age
- Email address and/or phone number
- Distance from ankle to bottom of the foot
- Distance from ankle to knee
- Distance from knee to hip

We will also ask you to review your phone screen answers, and confirm that the answers have not changed since the phone call.

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Sensors will be placed on your feet, calves, quads and around your sternum. We will place the kinematic and EMG sensors with adhesive tape. Once the sensors are confirmed to be working properly, you will stand relaxed on the force plates while we record the natural sway of your body. You will wear a safety harness and will be under close supervision by a research associate to aid in the case of a very unlikely fall. While wearing the harness, you will be asked to stand with your eyes open or closed, and on a varying thickness of foam that will range from no foam to a maximum of 2.4" of foam. Trials will be 60 seconds in duration and you will be given at least 30 seconds of rest between sets of six trials. You will also be given the opportunity for seated rest whenever you choose. Each of the conditions will be repeated three times. During these trials, we will monitor muscle activity, movement, and forces, as described below. In addition, we will use a video camera to record all trials. The trials are being recorded so that the investigators can view them if any trials produce unexpected results. These recordings will be completely secured and only accessible by members of the research team. These recording will have sound due to the nature of the video camera, but the audio recordings will not be used for any purpose.

Assessment of Muscle Activity: Our EMG system (Bagnoli™ Desktop EMG – 8 Channels) measures your muscle activity. Non-invasive surface electrodes are applied on your skin over your muscle. Alcohol wipes and/or a pumice stone are used to clean your skin and then an electrode unit is placed over each area. Lower leg and thigh muscles will be monitored, including anterior tibialis, gastrocnemius, quadriceps, and hamstrings. Our EMG system gathers information from your muscles but does not give any feedback back to you. Application of the electrodes takes 10-15 minutes.

Assessment of Heart Activity: Similar to the assessment of muscle activity, heart activity will be assessed using our EMG system (Bagnoli Desktop EMG – 8 Channels). Alcohol wipes and/or a pumice stone are used to clean your skin and then an electrode unit is placed around your sternum to record your pulse. Our EMG system gathers information from your muscles but does not give any feedback back to you. Application of the electrodes takes 5 minutes.

Assessment of Movement: Our motion capture system (NDI Optotrak Certus) measures the movement of your body while you perform a task. We will place markers on your skin and record the movement of those markers. The location of the markers will be feet, calves, quadriceps, sternum, and lower back. The application of the markers takes approximately 15 minutes.

Assessment of Force: Our force plate system (AMTI OR6) measures the forces your feet exert on the floor while you perform a task. The force plates are mounted in the floor. You will be standing barefoot on the force plates or standing on top of foam that is placed on top of the force plate. The surfaces are sterilized in between each subject.

RISKS

Understand that there may be possible risks for participating.

- Postural Control: There may be a risk of falling during the balance testing but this risk will be minimized by close monitoring from a research associate and a safety harness that will catch you in the event of a fall.
- EMG: There are no known risks to the use of EMGs. There may be skin irritation under the electrodes.
- Movement testing: There are no known risks to movement tracking. You may experience mild skin irritation in the area the markers were applied.
- Force testing: There are no known risks to force testing.

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BENEFITS
There are no direct benefits to you for participating in this study. It is anticipated that information gathered in this study will contribute to current scientific knowledge of quiet standing in healthy individuals under normal stance conditions and more challenging conditions created by the foam surface.

PAYMENT TO PARTICIPANTS
There are no costs or payments for participating in this study.

PARTICIPANT CONFIDENTIALITY
The researchers will protect your information, as required by law. Absolute confidentiality cannot be guaranteed because persons outside the study team may need to look at your study records. Your name or any information that reveals your identity will not be associated in any report, publication or presentation with the information collected about you or with the research findings from this study. Instead, the researcher(s) will use a study number rather than your name. Your identifiable information will not be shared unless (a) it is required by law or university policy, or (b) you give written permission.

Your study-related health information will be used at the Biodynamics Research Lab by Dr. Luchies, members of the research team, the KU Human Subjects Committee and other committees and offices that review and monitor research, if a regulatory review takes place.

All study information that is sent outside the Biodynamics Research Lab will have your name and all other identifying characteristics removed, so that your identity will not be known. Because identifiers will be removed, your health information will not be re-disclosed by outside persons or groups and will not lose its federal privacy protection.

Your permission to use and disclose your health information remains in effect until the study is complete and the results are analyzed. After that time, information and video recordings that personally identifies you will be removed from the study records.

INSTITUTIONAL DISCLAIMER STATEMENT
In the event of injury, the Kansas Tort Claims Act provides for compensation if it can be demonstrated that the injury was caused by the negligent or wrongful act or omission of a state employee acting within the scope of his/her employment.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION
You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION
You understand that your participation in this study is voluntary and that the choice not to participate or to quit at any time can be made without penalty or loss of benefits. The entire study may be discontinued for any reason without your consent by the investigator conducting the study.

You have a right to change your mind about allowing the research team to have access to your health information. If you want to cancel permission to use your health information, you should send a written request to Dr. Luchies. The mailing address is Carl Luchies PhD, 3135B Learned Hall, Lawrence, KS 66045.

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If you cancel permission to use your health information, you will be withdrawn from the study. The research team will stop collecting any additional information about you. The research team may use and share information that was gathered before they received your cancellation.

QUESTIONS ABOUT PARTICIPATION

You have read the information in this from. Dr. Luchies or his associates have answered your questions to your satisfaction. You know that if you have more questions after signing this form, you may contact Dr. Luchies at (785) 864-2993 or luchies@ku.edu. If you have questions about your rights as a research subject, you may call or write the Human Research Protection Program (HRPP) at (785) 864-7429 or 2385 Irving Hill Road, Lawrence, KS 66045.

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KEEP THIS SECTION FOR YOUR RECORDS. IF YOU WISH TO PARTICIPATE, PLEASE TEAR OFF THE FOLLOWING PAGE AND RETURN IT TO THE RESEARCHER(S).

KU Lawrence IRB # STUDY00141250 | Approval Period 9/20/2019 – 9/19/2020

"Quiet Standing Analysis during Somatosensory and Visual Deficiencies"

IRB # 00141250

PARTICIPANT CERTIFICATION:

If you agree to participate in this study please sign where indicated, then tear off this section and return it to the investigator(s). Keep the consent information for your records.

I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study and the use and disclosure of information about me for the study.

I agree to take part in this study as a research participant. By my signature, I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form.

_____	_____
Type/Print Participant's Name	Participant Number
_____	_____
Participant's Signature	Date

Phone Screen Form

Phone Screen Answers Healthy Foam Study

Interviewer:
_____

Date:
_____

Oral Consent: YES NO

Participant Information
Name:
_____

Email Address or Phone Number:
_____

Gender: Male Female Other

Question	YES	NO	When? Or Notes
Have you had any head injuries or concussions?			
Have you ever experienced any dizziness or fainting spells?			
Do you have osteoporosis in lower extremity joints (hip, knees, ankles, foot)?			
Have you had, or do you have arthritis in your legs that limits mobility or causes pain?			
Have you had, or do you have any hip, knee, ankle, or foot problems or injuries that limit mobility or cause pain?			
Do you have back problems that limit mobility or cause pain?			
Do you have nerve damage that is affecting your legs?			
Have you had, or do you have muscle problems in your legs that limit mobility or causes pain?			
Have you ever broken any bones in your legs, ankles, or feet?			
have you ever broken any bones in your spine?			
Have you had, or do you suffer from fibromyalgia? Or, have you had, or do you have constant muscle fatigue or aches in your body?			
Do you have any joint replacement in your leg joints?			
Do you have any joint fusion?			
Have you had, or do you have poor circulation in your legs that causes them to be cold or numb?			
Have you had, or do you have any lung disease (besides asthma?)			

Phone Screen Answers Healthy Foam Study

Have you had, or do you have any heart problems?			
Have you had, or do you have any chest pain from heart disease?			
Have you had, or do you have any vascular problems?			
Have you ever had a heart attack?			
Do you have high blood pressure? If yes, are you taking medication?			
Do you have any neurological disease?			
Do you suffer from Parkinson's disease?			
have you ever had a stroke?			
If subject is female : Are you pregnant?			
Any other issues we haven't mentioned that we should know about?			

Inclusion/Exclusion Criteria

Standing Foam Study				
Inclusion/Exclusion Criteria: Phone Screen				
Question	YES	NO	When?	Exclude?
Have you had any head injuries or concussions?				Yes if less than 1 yr ago
Have you ever experienced any dizziness or fainting spells?				Case-by-case decision
Do you have osteoporosis in lower extremity joints (hip, knees, ankles, foot)?				Yes
Have you had, or do you have arthritis in your legs that limits mobility or causes pain?				Yes if less than 1 yr ago
Have you had, or do you have any hip, knee, ankle, or foot problems or injuries that limit mobility or cause pain?				Yes if less than 1 yr ago
Do you have back problems that limit mobility or cause pain?				Yes if less than 1 yr ago
Do you have nerve damage that is affecting your legs?				Yes
Have you had, or do you have muscle problems in your legs that limit mobility or causes pain?				Yes if less than 1 yr ago
Have you ever broken any bones in your legs, ankles, or feet?				Yes if less than 2 yr ago
have you ever broken any bones in your spine?				Yes if less than 2 yr ago
Have you had, or do you suffer from fibromyalgia? Or, have you had, or do you have constant muscle fatigue or aches in your body?				Yes
Do you have any joint replacement in your leg joints?				Yes
Do you have any joint fusion?				Yes
Have you had, or do you have poor circulation in your legs that causes them to be cold or numb?				Yes
Have you had, or do you have any lung disease (besides asthma?)				Yes if severe
Have you had, or do you have any heart problems?				Yes if also yes to below
Have you had, or do you have any chest pain from heart disease?				Yes
Have you had, or do you have any vascular problems?				Yes
Have you ever had a heart attack?				Yes if less than 6 mo ago
Do you have high blood pressure? If yes, are you taking medication?				No by itself
Do you have any neurological disease?				Yes
Do you suffer from Parkinson's disease?				Yes
have you ever had a stroke?				Yes
If subject is female : Are you pregnant?				Yes
Any other issues we haven't mentioned that we should know about?				Case-by-case decision

Participant Information Collection Form

Participants Information Healthy Foam Study

Interviewer:
_____

Date:
_____

Signed Consent: YES NO

Phone Screen Answers Review
Have the answers from the phone screen changed from the day of the coversation to today? YES NO

If yes, what has changed?
_____

_____

Participant Information
Name:
_____ Number:
_____

Email Address or Phone Number:
_____

Gender: Male Female Other

Height:
_____

Weight:
_____

Age:
_____

Distance from ankle to bottom of the foot:
_____

Distance from ankle to knee:
_____

Distance from knee to hip:
_____

Appendix D: SA 3 Experimental Protocol Documents

Informed Consent

KU SCHOOL OF ENGINEERING
The University of Kansas

Adult Informed Consent Statement

"Quiet Standing Analysis during Vibrotactile Sensory Augmentation at the Feet"

KEY INFORMATION
Your participation in this research study is completely voluntary. The alternative to participation in this study is to not participate. The study team members will explain the study in detail and will answer any questions you might have.

The purpose of this study is to investigate the effect of vibration on stance and balance. Participating in the study will take a total of 4 hours, spread over 4 separate visits (1 hour/day) that are at least 2 days apart. You will be asked to do the following:

- stand on a flat, weight scale-like surface to measure your balance
- stand on a mat that will lightly vibrate the bottom of your feet. Please note: vibration used in this study will not exceed that of a common cellphone or video game controller.
- stand on soft foam which thickness is no more than 1 inch.
- respond if sensation is felt at one of your feet when an investigator gently pokes your foot.
- complete a standard 3-meter walking test on flat ground

More detailed information on the procedures can be found below.

Risks and side effects related to this study are considered minimal and non-significant, including:

- Falls (avoided with the use of an overhead harness)
- Skin irritation from adhesive stickers from EMG electrodes, motion tracking markers or plastic sticks used to check for sensation deficits (avoided by using medical grade materials)

Your identifiable information may be removed from the data collected during this project, and the de-identified data may be used for future research without any additional consent from you.

There are no direct benefits from participating in the study. However, this study will help doctors and engineers learn more about the effect of vibration on balance, informing potential future treatment strategies for patients with balance deficits.

INTRODUCTION
The Biodynamics Research Laboratory at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and choose not to participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time without retributions. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY
The purpose of this project is to gain a better understanding of the body's postural response to vibration at the feet, which has been proposed as a possible treatment for somatosensory (touch) deficiencies at the feet. It is expected that the results from this study will help us to better understand the contributions of somatosensory feedback in healthy standing balance. In the future, we aim to investigate the improved method on patient populations (e.g. diabetes, stroke, Parkinson's disease) to

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determine if any balance improvements are retained. Our long-term goal is to develop a new clinical intervention that could be used as a balance rehabilitation tool to reduce the risk of the falling in affected populations.

During this study, movement, force, and electromyography (EMG - muscle and heart activity) data could be collected from healthy adults during quiet standing on a flat surface with or without foam while their eyes are open or closed. All tests are non-invasive and considered to be low-risk to the participant. Data will be collected before, during and after vibration (less than or equal to that of a cell phone) is applied to the feet. The results from each testing session will provide the investigators with information about the how the vibration affects the participant's balance.

PROCEDURES

For this study, we will look at your quiet standing balance. First, you will be asked to change into your personal attire (shorts and t-shirt) that will allow us to easily place the sensors on your skin in the correct locations. Shorts and/or t-shirt will be needed if all sensors are to be used in your visits. You will be notified before your visits if shorts and/or t-shirt are necessary. Next, we will record the following demographic and physical information:

- Name
- Gender
- Height
- Weight
- Age
- Email address and/or phone number

If kinematic sensors will be used, they will be placed on your feet, calves, quads and around your sternum. We will place the kinematic and EMG sensors onto your body with medically approved adhesive tape. Once the sensors are calibrated, you will stand relaxed on the force plates (with or without foam) while we record the natural sway of your body both with your eyes open and closed. You will wear a safety harness and will be under close supervision by a research associate to minimize the risk of falling. Then you will be asked to stand on a mat (with or without foam) that will lightly vibrate your feet. After an initial calibration phase, the vibration will become unperceivable to you as it will be below your unique level of physical sensation. You will then complete the same standing balance task, under eyes open and eyes closed conditions, at multiple time points following vibration and once when the vibration is administered to you. Standing trials will be 90 seconds in duration and you will be given at least 30 seconds of rest between trials. You also have the opportunity to rest whenever you choose. During these trials, we will monitor muscle activity, movement, and forces, as described below. In addition, before your feet are vibrated, you will complete a 3-meter walking task known as the Time-Up-And-Go (TUG) test, and a foot sensation test known as the Semmes-Weinstein Monofilament (SWM) Test. Finally, we will use a video camera to record audio and video of all trials. The trials are being recorded so that the investigators can view them if any trials produce unexpected results. These recordings will be completely confidential, will only be accessible by members of the research team, and will not be used for any purpose unrelated to the research of the Biodynamics Research Lab.

Assessment of Muscle Activity: The EMG system (Bagnoli™ Desktop EMG – 8 Channels) measures the electrical activity of your muscles with non-invasive surface electrodes that are applied on your skin over your muscle. Alcohol wipes and/or a pumice stone are used to clean your skin prior to an electrode being placed over each area. Lower leg and thigh muscles will be monitored, including anterior tibialis, gastrocnemius, quadriceps, and hamstrings. The EMG system gathers information from your muscles but does not give any feedback back to you. Application of the electrodes takes no more than 10-15 minutes if all muscles and both legs are used. All sensors are sterilized between each participant.

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Assessment of Heart Activity: Similar to the assessment of muscle activity, heart activity will be assessed using the EMG system (Bagnoli Desktop EMG – 8 Channels). Alcohol wipes and/or a pumice stone will be used to clean your skin prior to an electrode unit being placed around your sternum to record your pulse. The EMG system gathers information from your muscles but does not give any feedback back to you. Application of the chest electrodes takes up to 5 minutes. All sensors are sterilized between each participant.

Assessment of Movement: The motion capture system (NDI Optotrak Certus) measures the movement of your body while you perform a task. We will place reflective markers on your skin and record the movement of those markers using motion capture cameras. The locations of the markers include feet, calves, quadriceps, sternum, and lower back. The application of the markers takes approximately 15 minutes. All sensors are sterilized between each participant.

Assessment of Force: The force plate system (AMTI OR6) measures the forces your feet exert on the floor while you perform a task. The force plates are mounted in the floor. You will be standing barefoot on the force plates. The surfaces are sterilized in between each participant.

Vibrating Mat: The mat you will stand on is a custom-designed system with embedded motors that can produce vibrations with varying pre-determined characteristics. The mat will be temporarily affixed to the floor during testing. You will be standing barefoot on the vibratory mat. The surfaces are sterilized in between each participant.

Postural Stability Scales: The TUG and SWM tests are quick medical tests that state if a participant is healthy or not. The TUG is a simple, non-invasive balance metric that takes less than a couple of minutes to complete. It requires you, starting in a sitting position, to stand up, walk 3 meters (10 feet), turn, walk back to the chair, and sit down. The SWM test requires you to sit with your eyes closed and respond "Yes" when you feel the investigator lightly poked you in one your feet. The touching probe is manufactured with medical accepted materials. meaning that allergies are not expected.

RISKS

Understand that there may be possible risks for participating in this study, although we expect them to be limited and non-significant due to safety precautions that will be enforced.

- Postural Control: There may be a risk of falling during the balance testing. This risk will be minimized by close monitoring from a research associate and a safety harness that will catch you in the event of a fall.
- Standing on Foam: Even though it feels different to stand on a foam with your eyes closed, after conducting standing trials on foam for over 2 years on another study, we have not had any short-term or long-term issues with our participant.
- EMG: There are no known risks to the use of EMGs. Minimal skin irritation may occur at the sites of electrode placement. The risk will be reduced by only using medical grade tape to attach the sensors to your skin.
- Movement testing: There are no known risks to movement tracking. You may experience mild skin irritation in the area the markers were applied. The risk will be reduced by only using medical grade tape to attach the sensors to your skin.

- Force testing: There are no known risks to force testing. You will wear a ceiling-mounted safety harness during standing balance trials. All surfaces of the force plates will be disinfected between participants.
- Vibratory stimulation: There are no known risks of vibrotactile stimulation. Previous studies have shown an improvement or no change in balance during and briefly following vibration. All surfaces of the vibratory mat will be disinfected between participants.
- Timed-Up-and-Go Test (TUG): There are no known risks to the TUG test, since it represents common everyday activities. You will have plenty of space to walk and turn, and at all times there will be a researcher making sure that you are safe.
- Semmes-Weinstein Monofilament (SWM) Test: There are no known risks to the SWM test; however, there is a small chance of skin irritation due to the touch between the touching probe and the skin. The risk will be reduced by only using medical grade materials to poke your skin.

BENEFITS

There are no direct benefits to you for participating in this study. It is anticipated that results from this study will lead to future development of improved intervention programs for somatosensory and/or balance impairments.

PAYMENT TO PARTICIPANTS

There are no costs or payments for participating in this study.

PARTICIPANT CONFIDENTIALITY

The researchers will protect your information, as required by law. Your name or any information that reveals your identity will not be associated with the research findings from this study in any report, publication, or presentation. Instead, the researcher(s) will use a study number rather than your name. Please note, however, that absolute confidentiality cannot be guaranteed in case persons outside the study team may need to look at your records for unforeseen circumstances. Your identifiable information will not be shared unless (a) it is required by law or university policy, or (b) you give written permission.

Your study-related health information will be used at the Biodynamics Research Lab by Dr. Luchies, members of the research team, the KU Human Subjects Committee, and other committees and offices that review and monitor research, if a regulatory review takes place.

All study information that is sent outside the Biodynamics Research Lab will have your name and all other identifying characteristics removed, so that your identity will not be known. Because identifiers will be removed, your health information will not be re-disclosed by outside persons or groups and will not lose its federal privacy protection.

Your permission to use and disclose your health information remains in effect until the study is complete and the results are analyzed. After that time, information and video recordings that personally identifies you will be removed from the study records.

INSTITUTIONAL DISCLAIMER STATEMENT

In the event of injury, the Kansas Tort Claims Act provides for compensation if it can be demonstrated that the injury was caused by the negligent or wrongful act or omission of a state employee acting within the scope of his/her employment.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION
You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION
You understand that your participation in this study is voluntary and that the choice not to participate or to quit at any time can be made without penalty or loss of benefits. In addition, testing sessions or the entire study may be discontinued for any reason without your consent by the investigator(s).

You have a right to change your mind about allowing the research team to have access to your health information. If you want to cancel permission to use your health information, you should send a written request to Dr. Luchies. The mailing address is: Carl Luchies PhD, 3135B Learned Hall, Lawrence, KS 66045. If you cancel permission to use your health information, you will be withdrawn from the study. The research team will stop collecting any additional information about you. The research team may use and share information that was gathered before they received your cancellation.

QUESTIONS ABOUT PARTICIPATION
Signing this form of consent indicates that you have read the information included within this from, and that Dr. Luchies or the research assistants have fully answered your questions to your satisfaction. You are aware that if you have more questions after signing this form, you may contact Dr. Luchies at (785) 864-2993 or luchies@ku.edu. If you have questions about your rights as a research subject, you may call or write the Human Research Protection Program (HRPP) at (785) 864-7429 or 2385 Irving Hill Road, Lawrence, KS 66045.

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*****KEEP THIS SECTION FOR YOUR RECORDS. IF YOU WISH TO PARTICIPATE, PLEASE TEAR OFF THE FOLLOWING PAGE, SIGN YOUR NAME, AND RETURN IT TO THE RESEARCHER(S).*****

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KU SCHOOL OF ENGINEERING
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"Quiet Standing Analysis during Vibrotactile Sensory Augmentation at the Feet"

IRB # 00144106

PARTICIPANT CERTIFICATION:

If you agree to participate in this study please sign where indicated, then tear off this section and return it to the investigator(s) of the KU Biodynamics Research Lab. Keep the consent information for your records.

By signing below, I agree that I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received satisfactory answers to, any questions I had regarding the study and the use and disclosure of information about me for the study.

I agree to take part in this study as a research participant. By my signature, I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form.

Type/Print Participant's Name	Participant Number
Participant's Signature	Date

Type/Print Overseeing Research Investigator's Name

Research Investigator's Signature	Date

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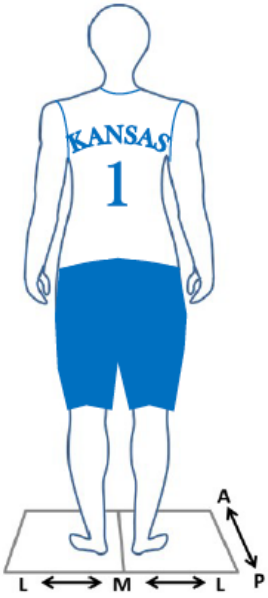
Recruitment Flyer

Research Subjects Needed



Does Vibration at the Feet Improve Standing Balance?

Research participants are needed for a low risk, non-invasive study that will investigate the contributions and retention of sub-sensory vibration to postural sway in standing balance. Quiet standing data will be collected under two visual conditions (eyes open and eyes closed) before and after the feet are mechanically vibrated (no more than the vibration of a cell phone).

Time Commitment: Four (4) 60-minute sessions at least 2 days apart.

Eligibility: Adults ages 18 - 65 with no significant history of musculoskeletal, neurologic, vestibular or mobility deficiencies. Females who are pregnant or plan to become pregnant are not eligible to participate.

Benefits: There are no direct benefits to participants in this study.

Risks: This study is non-invasive and minimal risk. Any relevant risks that participants may experience will be discussed prior to beginning the experiment, as well as precautions in place to ensure subject safety.

Significance: It is expected that the results of this study will guide researchers in developing improved therapeutic interventions to improve quality of life for fall-risk populations.

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Biodynamics Research Lab
PI: Carl Luchies, PhD

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1530 W 15th St., Lawrence, KS

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Biodynamics Research Lab
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Phone Screen

Phone Screen Answers — Heatlhy Vibrotactile Stimulation Study

Interviewer: _____

Date: _____

Oral Consent: YES NO

Participant Information

Name: _____

Email Address or Phone Number: _____

Gender: Male Female Other

Question	YES	NO	When? Or Notes
Have you had any head injuries or concussions?			
Have you ever experienced any dizziness or fainting spells?			
Do you have osteoporosis in lower extremity joints (hip, knees, ankles, foot)?			
Have you had, or do you have arthritis in your legs that limits mobility or causes pain?			
Have you had, or do you have any hip, knee, ankle, or foot problems or injuries that limit mobility or cause pain?			
Do you have back problems that limit mobility or cause pain?			
Do you have nerve damage that is affecting your legs?			
Have you had, or do you have muscle problems in your legs that limit mobility or causes pain?			
Have you ever broken any bones in your legs, ankles, or feet?			
have you ever broken any bones in your spine?			
Have you had, or do you suffer from fibromyalgia? Or, have you had, or do you have constant muscle fatigue or aches in your body?			
Do you have any joint replacement in your leg joints?			
Do you have any joint fusion?			
Have you had, or do you have poor circulation in your legs that causes them to be cold or numb?			
Have you had, or do you have any lung disease (besides asthma?)			
Have you had, or do you have any heart problems?			
Have you had, or do you have any chest pain from heart disease?			
Have you had, or do you have any vascular problems?			

Phone Screen Answers

Heatlhy Vibrotactile Stimulation Study

Have you ever had a heart attack?			
Do you have high blood pressure? If yes, are you taking medication?			
Do you have any neurological disease?			
Do you suffer from Parkinson's disease?			
have you ever had a stroke?			
If subject is female : Are you pregnant?			
Any other issues we haven't mentioned that we should know about?			

Inclusion/Exclusion Criteria

Heatlhy Vibrotactile Stimulation Study				
Inclusion/Exclusion Criteria: Phone Screen				
Question	YES	NO	When?	Exclude?
Have you had any head injuries or concussions?				Yes if less than 1 yr ago
Have you ever experienced any dizziness or fainting spells?				Case-by-case decision
Do you have osteoporosis in lower extremity joints (hip, knees, ankles, foot)?				Yes
Have you had, or do you have arthritis in your legs that limits mobility or causes pain?				Yes if less than 1 yr ago
Have you had, or do you have any hip, knee, ankle, or foot problems or injuries that limit mobility or cause pain?				Yes if less than 1 yr ago
Do you have back problems that limit mobility or cause pain?				Yes if less than 1 yr ago
Do you have nerve damage that is affecting your legs?				Yes
Have you had, or do you have muscle problems in your legs that limit mobility or causes pain?				Yes if less than 1 yr ago
Have you ever broken any bones in your legs, ankles, or feet?				Yes if less than 2 yr ago
have you ever broken any bones in your spine?				Yes if less than 2 yr ago
Have you had, or do you suffer from fibromyalgia? Or, have you had, or do you have constant muscle fatigue or aches in your body?				Yes
Do you have any joint replacement in your leg joints?				Yes
Do you have any joint fusion?				Yes
Have you had, or do you have poor circulation in your legs that causes them to be cold or numb?				Yes
Have you had, or do you have any lung disease (besides asthma?)				Yes if severe
Have you had, or do you have any heart problems?				Yes if also yes to below
Have you had, or do you have any chest pain from heart disease?				Yes
Have you had, or do you have any vascular problems?				Yes
Have you ever had a heart attack?				Yes if less than 6 mo ago
Do you have high blood pressure? If yes, are you taking medication?				No by itself
Do you have any neurological disease?				Yes
Do you suffer from Parkinson's disease?				Yes
have you ever had a stroke?				Yes
If subject is female : Are you pregnant?				Yes
Any other issues we haven't mentioned that we should know about?				Case-by-case decision

Participant Information Collection Form

Participants Information — Vibrotactile Stimulation Study

Participant Information	**IRB Study 00144106**
Name: _____	Subject ID: _____
Email Address or Phone Number: _____	Session Order (1-5): _____
Gender: Male Female Other	Session Number (1-4): _____
Height: _____ Age: _____	Noise Type ID: _____ *White (WH), Pink (PK), Brown (BR), Placebo (PB)*
Weight: (n/a - will be calculated via Baseline)	Visual Condition Order: (Circle) 1 2 3 4 5
Shoe Size *(Circle)* Men's Women's Size _____	Length Classification: *(Circle)* Short Middle Long *Short: Men's 7-8.5, Women's 6-9 Middle: Men's 9-10.5, Women's 9.5-11.5 Long: Men's 11-14, Women's 12-14*
Phone Screen Answers Review	
Interviewer: _____	Date (DDMMMYEAR): _____
Have the answers from the phone screen changed from the day of the coversation to today? *(Circle)* YES NO	Has food intake been normal? *(Circle)* YES NO
If yes, what has changed? _____ _____	Participant Has Signed Consent: *(Circle)* YES NO
Data Collection Information	
Threshold (VPT) = _____Motor, _____ % Power	TUG Baseline: _____ (sec)
Stimulation = _____ Motor, _____ % Power (90% VPT)	SWM Test: _____
Threshold Trial(s) Notes:	**Other Notes:**

Notice of Deception

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Post Evaluation: Notice of Deception

"Quiet Standing Analysis during Vibrotactile Sensory Augmentation at the Feet"

APPRECIATION
The members of the Biodynamics Research Lab Team would like to sincerely thank you for participating in this ongoing research study! Your contributions to the scientific community will allow us to better understand the effects of vibration on standing balance, and to utilize this information to benefit society through innovative balance rehabilitation tools.

DECLARATION
At this point, we are required by the University of Kansas Institutional Review Board to inform you that deception was utilized during parts of this research study.

DESCRIPTION
Over the course of this study, you experienced three types of vibration beneath your feet during three different testing sessions. During a fourth testing session, which was positioned randomly amongst the other three sessions, we applied a fake vibration treatment. There was no vibration beneath your feet at this time. We collected the same information about your balance following each of the real and fake vibrations. This information will be used to better understand the effects of vibration on healthy balance. We will compare the data collected from the fake vibration session to each of the three real vibration sessions. These comparisons may allow us to recognize psychological factors that could contribute to standing balance. The use of deception did not increase risk to you in any way.

CONSENT
You are reminded that you are free to withdraw from this study or any part of it at any time without retributions. Please refer to the Informed Consent form which was provided to you at the beginning of this study for more information.

CONFIRMATION
By signing below, you indicate that you have received a copy of the Notice of Deception. You also verify that a research team member has reviewed this document with you and has answered any questions you may have to the best of our capability without revealing intellectual property or potentially proprietary information. You have no further questions about the use of deception.

_____	_____	_____
Participant's Name	Initials	Date
_____	_____	_____
Witnessing Researcher	Initials	Date

Appendix E: MATLAB Code

COP Calculation Function

```
function [COPx,COPy,distance,xm,ym]=COP(force)

    COPx=[];
    COPy=[];

    Fx=force(:,1);
    Fy=force(:,2);
    Fz=force(:,3);
    Mx=force(:,4);
    My=force(:,5);
    dz=0.0381; % Kai's SOT force plate

    COPx=(-(My+Fx.*dz)./Fz)*100; %cm
    COPy=((Mx-Fy.*dz)./Fz)*100;

    xm=mean(COPx);
    ym=mean(COPy);

    % Distance traveled
    for i=1:length(COPx)-1
    x_travel(i)=COPx(i+1)-COPx(i);
    y_travel(i)=COPy(i+1)-COPy(i);
    distance(i)=sqrt((x_travel(i).^2)+(y_travel(i).^2));

end
```

Rambling-Trembling Decomposition Function

```
% Rambling-Trembling Analysis Function
% Purpose: Decompose COP signals into rambling and trembling components
% Written by: Eryn Gerber, erynbgerber@ku.edu
% Last Updated Sept 3, 2020

%%
% INPUT:
% force_series: nx1 array of force data over time
% COP_series: nx1 array of COP data over time
% time: nx1 timeseries

% OUTPUT:
% Rambling: RM timeseries
% Trembling: TR timeseries
% COP: COP timeseries

function [Rambling,Trembling,F_zero_index] =
RamblingTrembling(force_series,COP_series,time,trim)

len = length(force_series);
F_zero_index=[];
F_zero_COP=[];
F_zero_time=[];

for i=1:len-1
    if
or(and(force_series(i)<0,force_series(i+1)>0),and(force_series(i)>0,force_ser
ies(i+1)<0))
        [F_zero_index] = [F_zero_index;i];
        [F_zero_COP] = [F_zero_COP;COP_series(i)];
        [F_zero_time] = [F_zero_time;time(i)];
    end
end

% Function will return NaN if there are <2 zero-crossing points in the
dataset
if or(isempty(F_zero_index)== 1,size(F_zero_index)<2)
    disp('F never crosses 0')
    Rambling = NaN;
    Trembling = NaN;
    return
end

% Function will calculate Rambling-Trembling timeseries if F_zero_index is
% filled
if isempty(F_zero_index) == 0
    F_zero_COP_spline =
pchip(F_zero_time,F_zero_COP,time(F_zero_index(1):length(force_series)));
    Rambling = F_zero_COP_spline;
    if length(Rambling)>len-trim
        Rambling = Rambling(1:len-trim);
        Trembling = COP_series(1:len-trim)-Rambling;
```

```
    else
        Trembling = NaN;
        Rambling = NaN;
    end


end
```

COP Range Calculation Function

```
function [COP_range_x,COP_range_y] = COP_Range(COPx,COPy)
% SWAY RANGE %input = meters, output = cm
COPx_max        = max(COPx);
COPx_min        = min(COPx);
COPy_max        = max(COPy);
COPy_min        = min(COPy);
COP_range_x   = 100.*(COPx_max - COPx_min);
COP_range_y   = 100.*(COPy_max - COPy_min);
```

Sample Entropy Calculation Function

```
function SampEn=SampEn_Opt(data,m,R)
%% SampEn=SampEn_Opt(data,m,R)
%Optimized Sample Entropy of Time Series (Richman and Moorman)
%Camilo Giraldo (c318g339@ku.edu)
%The University of Kansas - Biodynamics Lab
%Last Udpate: 05/15/2018
%
%Acknowledgements: This code was originally created by J McCamley May
%on 2016. It was commented by Camilo Giraldo.
%
%Purpose: This code calcualtes the sample entropy (according to SampEn
%formula developed by Richman and Moorman, 2000) of a time series with a
%vector length m, and a radius of R times the standard devaiation of the
%time series. This function has been validated with SampEn_KU, and
%both functions give the same result. In addition, this function is faster
%than SampEn_KU. However, if it is desired to understand SampEn, it is
%recommended to use SampEn_KU since it goes step by step as described in
%Richman and Moorman, 2000.
%
%Inputs:
%   data: time series in column form
%   m:    vector length to form in sample entropy calculation
%   R:    R*std of the time series
%
%Output:
%   SampEn: sample entropy of the time series
%
%Reference:
%   Richman, J. S. American Journal of Physiology. Heart and Circulatory
%       Physiology: Physiological Time-Series Analysis using Approximate
%       Entropy and Sample Entropy. 278 Vol. American Physiological Society,
%       06/2000.
%   Stergiou, Nicholas. Nonlinear Analysis for Human Movement Variability.
%       2016. Print.

%% Beginning of function
% Define r as R times the standard deviation
r=R*std(data);

%Length of the time series
N=length(data);

%% Calculating of Bmr & Amr (Richman and Moorman, 2000)
%Preallocating space
dij=zeros(N-m,m+1);     %Difference matrix between vectors
% dj=zeros(N-m,1);
% dj1=zeros(N-m,1);
Bm=zeros(N-m,1);        %Bm array
Am=zeros(N-m,1);        %Am array

%Calculating Am and Bm
for ii = 1:N-m          %Chooses the vector that will be analyzed

    %Calculating difference matrix
```

```
    for kk = 1:m+1      %Number of elements in vectors to compare
        dij(:,kk)=abs(data(1+kk-1:N-m+kk-1)-data(ii+kk-1));
    end

    %Storing largest differences for Bm and Am
    dj=max(dij(:,1:m),[],2);    %Bm
    dj1=max(dij,[],2);          %Am

    %Counter number of matches for Bm and Am (self counted)
    d=find(dj<=r);              %Bm
    d1=find(dj1<=r);            %Am

    %Updating number of matches with no self counter for Bm and Am
    nm=length(d)-1;             %Bm
    nm1=length(d1)-1;           %Am

    %Probability Bm and Am for the vector just analyzed
    Bm(ii)=nm/(N-m);
    Am(ii)=nm1/(N-m);

end

%Calculating total Bmr and Amr
Bmr=sum(Bm)/(N-m);
Amr=sum(Am)/(N-m);

%% Sample Entropy (Richman and Moorman, 2000)
SampEn=-log(Amr/Bmr);

end
```

SA1 Main Analysis Code

```
%% Main_Sway_Analysis
% Written by Eryn Gerber (eryngerber@ku.edu)
% The University of Kansas - Biodynamics Lab
% Last updated 1/12/2021
%
% Purpose: This is the main script used to analyze the foam study data by
% calculating sample entropy and rms of COP, RM, and TR timeseries
clear; clc; close all;

% Sampling Parameters
fsample = 100; %[Hz]
fdown = 50; % The desired frequency (in Hz) after downsampling the data
trial_time = 60; %[s]
trial_dt = 1/fsample; %[s]
g = 9.80665; %[m/s^2]

% Force plate information
gain_fp = 1000;

%% Load Subject Information
subject_info = xlsread('/Users/eryngerber/Documents/Biodynamics Lab/Foam
2.0/Data/Raw Data/Subject_Data.xlsx',1,'B3:G54');
%% Establish the path to the data

path = '/Users/eryngerber/Documents/Biodynamics Lab/Foam 2.0/Data/Raw
Data/s';

% Choose the conditions of the trial(s) to be analyzed
maxsubj = 1052;
maxfoam = 4;
maxvision = 1;
maxtrial = 3;

% Initialize empty results matrices
all_data=zeros((maxfoam+1)*(maxvision+1)*maxtrial*length(subject_info),22);
all_data_trialavg = zeros((maxfoam+1)*(maxvision+1)*length(subject_info),21);

j=0;
ii=0;
for subject = 1001:maxsubj

    fprintf([datestr(clock,21) ' \n'])
    fprintf('subject %d\n',subject)


    % Read the zeros file and calculate the mean for each channel
    zeromean = mean(dlmread([path int2str(subject)
'/zeros000.txt'],'\t',1,0));

    % Initialize the count and set figure number to match subject number
    fignum=subject;
```

```
    count = 0;
    for numvision = 0:maxvision
        fprintf('vision %d\n',numvision)
        if numvision == 0
            vision = 'EC';
        else
            vision = 'EO';
        end
        for foam = 0:maxfoam
            fprintf('foam %d\n',foam)
            for trial = 1:maxtrial
                ii=ii+1;
                % Define the file to be analyzed and read the data
                fname = [path int2str(subject) '/Foam_' int2str(foam) '_'
vision '_' int2str(trial) '.txt'];
                data = dlmread(fname,'\t',1,0);

                % Apply a 15 Hz low-pass filter to the raw data
                order = 4; %fourth order filter
                cutoff_freq = 15; %cutoff frequency in Hz
                data=Low_Pass_Filt(order,cutoff_freq,fsample,data);

                % Downsample the time series to the desired sampling
frequency
                ratio = fsample/fdown;
                data = downsample(data, ratio);
                time = data(:,1);

                % Extract the appropriate subject info
                info=subject_info(subject-1000,:);
                age=info(2);
                gender=info(3); %0 or 1, 0=male
                height=info(4); %given in cm
                weight=info(5); %kg
                bmi=info(6);

                % Add to the count, used for the subplot function
                count = count+1;

                % Calibrate data from volts to force and moments for both FPs
                force_right = V2f_fp3364(data,zeromean,2:7);    %FP 3364
                force_left = V2f_fp3477(data,zeromean,8:13);   %FP 3477

                % Apply a 90deg CCW rotation about the z-axis to make +x the
                % anterior direction and +y to subject's right
                force_right=[-force_right(:,2) force_right(:,1)
force_right(:,3) ...
                    -force_right(:,5) force_right(:,4) force_right(:,6)];
%FP3364
                force_left=[-force_left(:,2) force_left(:,1) force_left(:,3)
...
                    -force_left(:,5) force_left(:,4) force_left(:,6)];
%FP3477

                % Combine calibrated force plate data together
```

```
                % Coordinate system is as above: +x=anterior, +y=subject's
right
                force_comb = comb_FPs(force_left, force_right);

                % Calculate COPx and COPy
                COP = comb_FPs_COP(force_comb);
                COP_AP=COP(:,1)-mean(COP(:,1)); % + = anterior
                COP_ML=COP(:,2)-mean(COP(:,2)); % + = subject's right

                %% Rambling-Trembling Decomposition
                % Centered force measurements - need to account for
                % positioning on FPs
                force_comb = force_comb-mean(force_comb);
                trim=100;

[RM_AP,TR_AP]=RamblingTrembling(force_comb(:,1),COP_AP,time,trim);

[RM_ML,TR_ML]=RamblingTrembling(force_comb(:,2),COP_ML,time,trim);

                % Trim first and last two seconds of all data
                COP = COP(trim:length(COP)-trim);
                force_comb = force_comb(100:2902);
                time = data(100:2902,1);
                %% Sample Entropy Calculations
                m = 2;
                r = 0.09855;
                SampEn_COP_AP = SampEn_Opt(COP_AP,m,r);
                SampEn_COP_ML = SampEn_Opt(COP_ML,m,r);
                SampEn_RM_AP = SampEn_Opt(RM_AP,m,r);
                SampEn_RM_ML = SampEn_Opt(RM_ML,m,r);
                SampEn_TR_AP = SampEn_Opt(TR_AP,m,r);
                SampEn_TR_ML = SampEn_Opt(TR_ML,m,r);

                %% RMS Calculations
                RMS_COP_AP = 100.*rms(COP_AP);
                RMS_COP_ML = 100.*rms(COP_ML);
                RMS_RM_AP = 100.*rms(RM_AP);
                RMS_RM_ML = 100.*rms(RM_ML);
                RMS_TR_AP = 100.*rms(TR_AP);
                RMS_TR_ML = 100.*rms(TR_ML);

                %% Range Calculations % cm
                [Range_COP_AP,Range_COP_ML] = COP_Range(COP_AP,COP_ML);
                [Range_RM_AP,Range_RM_ML] = COP_Range(RM_AP,RM_ML);
                [Range_TR_AP,Range_TR_ML] = COP_Range(TR_AP,TR_ML);

                %% Data Output
                all_data(ii,:) =
[subject,foam,numvision,trial,SampEn_COP_AP,SampEn_COP_ML,SampEn_RM_AP,SampEn
_RM_ML,SampEn_TR_AP,SampEn_TR_ML,RMS_COP_AP,RMS_COP_ML,RMS_RM_AP,RMS_RM_ML,RM
S_TR_AP,RMS_TR_ML,Range_COP_AP,Range_COP_ML,Range_RM_AP,Range_RM_ML,Range_TR_
AP,Range_TR_ML];

            end
            j=j+1;
```

```
            all_data_trialavg(j,:) =
[subject,foam,numvision,mean(all_data(ii-2:ii,5)),mean(all_data(ii-
2:ii,6)),mean(all_data(ii-2:ii,7)),mean(all_data(ii-
2:ii,8)),mean(all_data(ii-2:ii,9)),mean(all_data(ii-
2:ii,10)),mean(all_data(ii-2:ii,11)),mean(all_data(ii-
2:ii,12)),mean(all_data(ii-2:ii,13)),mean(all_data(ii-
2:ii,14)),mean(all_data(ii-2:ii,15)),mean(all_data(ii-
2:ii,16)),mean(all_data(ii-2:ii,17)),mean(all_data(ii-
2:ii,18)),mean(all_data(ii-2:ii,19)),mean(all_data(ii-
2:ii,20)),mean(all_data(ii-2:ii,21)),mean(all_data(ii-2:ii,22))];
    end
    end
end

%% Remove outlier subjects (s1022)
for i=1:length(all_data)
    if all_data(i,1)==1022
        all_data(i,:)=NaN;
    end
end

all_data(~any(~isnan(all_data), 2),:)=[];

%% Sorted Data
% All Data
all_data_byfoam = sortrows(all_data,2);
all_data_byvision = sortrows(all_data,3);

all_data_EC = all_data_byvision(1:(length(all_data)/2),:);
all_data_EC_byfoam = sortrows(all_data_EC,2);
len_foam = length(all_data_EC)/5;
all_data_EC_foam0 = all_data_EC_byfoam(1:len_foam,:);
all_data_EC_foam1 = all_data_EC_byfoam(len_foam+1:2*len_foam,:);
all_data_EC_foam2 = all_data_EC_byfoam(2*len_foam+1:3*len_foam,:);
all_data_EC_foam3 = all_data_EC_byfoam(3*len_foam+1:4*len_foam,:);
all_data_EC_foam4 = all_data_EC_byfoam(4*len_foam+1:5*len_foam,:);

all_data_EO = all_data_byvision((length(all_data)/2)+1:end,:);
all_data_EO_byfoam = sortrows(all_data_EO,2);
all_data_EO_foam0 = all_data_EO_byfoam(1:len_foam,:);
all_data_EO_foam1 = all_data_EO_byfoam(len_foam+1:2*len_foam,:);
all_data_EO_foam2 = all_data_EO_byfoam(2*len_foam+1:3*len_foam,:);
all_data_EO_foam3 = all_data_EO_byfoam(3*len_foam+1:4*len_foam,:);
all_data_EO_foam4 = all_data_EO_byfoam(4*len_foam+1:5*len_foam,:);

% Trial Averages
all_data_trialavg_byfoam = sortrows(all_data_trialavg,2);
all_data_trialavg_byvision = sortrows(all_data_trialavg,3);

all_data_trialavg_EC =
all_data_trialavg_byvision(1:length(all_data_trialavg_byvision)/2,:);
all_data_trialavg_EC_byfoam = sortrows(all_data_trialavg_EC,2);
len_foam_trialavg_EC = length(all_data_trialavg_EC)/5;
all_data_trialavg_EC_foam0 =
all_data_trialavg_EC_byfoam(1:len_foam_trialavg_EC,:);
```

```
all_data_trialavg_EC_foam1 =
all_data_trialavg_EC_byfoam(len_foam_trialavg_EC+1:2*len_foam_trialavg_EC,:);
all_data_trialavg_EC_foam2 =
all_data_trialavg_EC_byfoam(2*len_foam_trialavg_EC+1:3*len_foam_trialavg_EC,:
);
all_data_trialavg_EC_foam3 =
all_data_trialavg_EC_byfoam(3*len_foam_trialavg_EC+1:4*len_foam_trialavg_EC,:
);
all_data_trialavg_EC_foam4 =
all_data_trialavg_EC_byfoam(4*len_foam_trialavg_EC+1:5*len_foam_trialavg_EC,:
);

all_data_trialavg_EO =
all_data_trialavg_byvision((length(all_data_trialavg_byvision)/2)+1:end,:);
all_data_trialavg_EO_byfoam = sortrows(all_data_trialavg_EO,2);
all_data_trialavg_EO_foam0 =
all_data_trialavg_EO_byfoam(1:len_foam_trialavg_EC,:);
all_data_trialavg_EO_foam1 =
all_data_trialavg_EO_byfoam(len_foam_trialavg_EC+1:2*len_foam_trialavg_EC,:);
all_data_trialavg_EO_foam2 =
all_data_trialavg_EO_byfoam(2*len_foam_trialavg_EC+1:3*len_foam_trialavg_EC,:
);
all_data_trialavg_EO_foam3 =
all_data_trialavg_EO_byfoam(3*len_foam_trialavg_EC+1:4*len_foam_trialavg_EC,:
);
all_data_trialavg_EO_foam4 =
all_data_trialavg_EO_byfoam(4*len_foam_trialavg_EC+1:5*len_foam_trialavg_EC,:
);

%% Save Data as .mat files into results folder
save('/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 1 -
Nonlinear RM-TR/Processed
Data/Results/all_data.mat','all_data','all_data_EC','all_data_EO','all_data_t
rialavg');
save('/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 1 -
Nonlinear RM-TR/Processed
Data/Results/all_data_EC_byfoam.mat','all_data_EC_byfoam','all_data_EC_foam0'
,'all_data_EC_foam1','all_data_EC_foam2','all_data_EC_foam3','all_data_EC_foa
m4');
save('/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 1 -
Nonlinear RM-TR/Processed
Data/Results/all_data_EO_byfoam.mat','all_data_EO_byfoam','all_data_EO_foam0'
,'all_data_EO_foam1','all_data_EO_foam2','all_data_EO_foam3','all_data_EO_foa
m4');
save('/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 1 -
Nonlinear RM-TR/Processed
Data/Results/all_data_trialavg_EC.mat','all_data_trialavg_EC','all_data_trial
avg_EC_foam0','all_data_trialavg_EC_foam1','all_data_trialavg_EC_foam2','all_
data_trialavg_EC_foam3','all_data_trialavg_EC_foam4');
save('/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 1 -
Nonlinear RM-TR/Processed
Data/Results/all_data_trialavg_EO.mat','all_data_trialavg_EO','all_data_trial
avg_EO_foam0','all_data_trialavg_EO_foam1','all_data_trialavg_EO_foam2','all_
data_trialavg_EO_foam3','all_data_trialavg_EO_foam4');
```

SA1 Statistical Analysis

```
% Results_Stats
load('all_data_trialavg_EC.mat')
%% AP SE
F0_M1 = all_data_trialavg_EC_foam0(:,4);
F1_M1 = all_data_trialavg_EC_foam1(:,4);
F2_M1 = all_data_trialavg_EC_foam2(:,4);
F3_M1 = all_data_trialavg_EC_foam3(:,4);
F4_M1 = all_data_trialavg_EC_foam4(:,4);

F0_M2 = all_data_trialavg_EC_foam0(:,6);
F1_M2 = all_data_trialavg_EC_foam1(:,6);
F2_M2 = all_data_trialavg_EC_foam2(:,6);
F3_M2 = all_data_trialavg_EC_foam3(:,6);
F4_M2 = all_data_trialavg_EC_foam4(:,6);

F0_M3 = all_data_trialavg_EC_foam0(:,8);
F1_M3 = all_data_trialavg_EC_foam1(:,8);
F2_M3 = all_data_trialavg_EC_foam2(:,8);
F3_M3 = all_data_trialavg_EC_foam3(:,8);
F4_M3 = all_data_trialavg_EC_foam4(:,8);

W = table(categorical([0 0 0 1 1 1 2 2 2 3 3 3 4 4 4].'),categorical([1 2 3 1
2 3 1 2 3 1 2 3 1 2 3].'),'VariableNames',{'Foam','Meas'});

AP_SE_tbl =
table(F0_M1,F0_M2,F0_M3,F1_M1,F1_M2,F1_M3,F2_M1,F2_M2,F2_M3,F3_M1,F3_M2,F3_M3
,F4_M1,F4_M2,F4_M3,'VariableNames',{'F0_M1','F0_M2','F0_M3','F1_M1','F1_M2','
F1_M3','F2_M1','F2_M2','F2_M3','F3_M1','F3_M2','F3_M3','F4_M1','F4_M2','F4_M3
'});

AP_SE_rm = fitrm(AP_SE_tbl,'F4_M3-F0_M1 ~ 1','WithinDesign',W);
[p1,ranovatbl_AP_SE_stats] = ranova(AP_SE_rm,'withinmodel','Foam*Meas');
results_AP_SE=multcompare(AP_SE_rm,'Meas','By','Foam');

%% ML SE
F0_M1 = all_data_trialavg_EC_foam0(:,5);
F1_M1 = all_data_trialavg_EC_foam1(:,5);
F2_M1 = all_data_trialavg_EC_foam2(:,5);
F3_M1 = all_data_trialavg_EC_foam3(:,5);
F4_M1 = all_data_trialavg_EC_foam4(:,5);

F0_M2 = all_data_trialavg_EC_foam0(:,7);
F1_M2 = all_data_trialavg_EC_foam1(:,7);
F2_M2 = all_data_trialavg_EC_foam2(:,7);
F3_M2 = all_data_trialavg_EC_foam3(:,7);
F4_M2 = all_data_trialavg_EC_foam4(:,7);
```

```
F0_M3 = all_data_trialavg_EC_foam0(:,9);
F1_M3 = all_data_trialavg_EC_foam1(:,9);
F2_M3 = all_data_trialavg_EC_foam2(:,9);
F3_M3 = all_data_trialavg_EC_foam3(:,9);
F4_M3 = all_data_trialavg_EC_foam4(:,9);

W = table(categorical([0 0 0 1 1 1 2 2 2 3 3 3 4 4 4].'),categorical([1 2 3 1
2 3 1 2 3 1 2 3 1 2 3].'),'VariableNames',{'Foam','Meas'});

ML_SE_tbl =
table(F0_M1,F0_M2,F0_M3,F1_M1,F1_M2,F1_M3,F2_M1,F2_M2,F2_M3,F3_M1,F3_M2,F3_M3
,F4_M1,F4_M2,F4_M3,'VariableNames',{'F0_M1','F0_M2','F0_M3','F1_M1','F1_M2','
F1_M3','F2_M1','F2_M2','F2_M3','F3_M1','F3_M2','F3_M3','F4_M1','F4_M2','F4_M3
'});

ML_SE_rm = fitrm(ML_SE_tbl,'F4_M3-F0_M1 ~ 1','WithinDesign',W);
[p1,ranovatbl_ML_SE_stats] = ranova(ML_SE_rm,'withinmodel','Foam*Meas');
results_ML_SE=multcompare(ML_SE_rm,'Meas','By','Foam');

%% AP RMS
F0_M1 = all_data_trialavg_EC_foam0(:,10);
F1_M1 = all_data_trialavg_EC_foam1(:,10);
F2_M1 = all_data_trialavg_EC_foam2(:,10);
F3_M1 = all_data_trialavg_EC_foam3(:,10);
F4_M1 = all_data_trialavg_EC_foam4(:,10);

F0_M2 = all_data_trialavg_EC_foam0(:,12);
F1_M2 = all_data_trialavg_EC_foam1(:,12);
F2_M2 = all_data_trialavg_EC_foam2(:,12);
F3_M2 = all_data_trialavg_EC_foam3(:,12);
F4_M2 = all_data_trialavg_EC_foam4(:,12);

F0_M3 = all_data_trialavg_EC_foam0(:,14);
F1_M3 = all_data_trialavg_EC_foam1(:,14);
F2_M3 = all_data_trialavg_EC_foam2(:,14);
F3_M3 = all_data_trialavg_EC_foam3(:,14);
F4_M3 = all_data_trialavg_EC_foam4(:,14);

W = table(categorical([0 0 0 1 1 1 2 2 2 3 3 3 4 4 4].'),categorical([1 2 3 1
2 3 1 2 3 1 2 3 1 2 3].'),'VariableNames',{'Foam','Meas'});

AP_RMS_tbl =
table(F0_M1,F0_M2,F0_M3,F1_M1,F1_M2,F1_M3,F2_M1,F2_M2,F2_M3,F3_M1,F3_M2,F3_M3
,F4_M1,F4_M2,F4_M3,'VariableNames',{'F0_M1','F0_M2','F0_M3','F1_M1','F1_M2','
F1_M3','F2_M1','F2_M2','F2_M3','F3_M1','F3_M2','F3_M3','F4_M1','F4_M2','F4_M3
'});

AP_RMS_rm = fitrm(AP_RMS_tbl,'F4_M3-F0_M1 ~ 1','WithinDesign',W);
[p1,ranovatbl_AP_RMS_stats] = ranova(AP_RMS_rm,'withinmodel','Foam*Meas');
results_AP_RMS=multcompare(AP_RMS_rm,'Meas','By','Foam');

%% ML RMS
F0_M1 = all_data_trialavg_EC_foam0(:,11);
F1_M1 = all_data_trialavg_EC_foam1(:,11);
```

```
F2_M1 = all_data_trialavg_EC_foam2(:,11);
F3_M1 = all_data_trialavg_EC_foam3(:,11);
F4_M1 = all_data_trialavg_EC_foam4(:,11);

F0_M2 = all_data_trialavg_EC_foam0(:,13);
F1_M2 = all_data_trialavg_EC_foam1(:,13);
F2_M2 = all_data_trialavg_EC_foam2(:,13);
F3_M2 = all_data_trialavg_EC_foam3(:,13);
F4_M2 = all_data_trialavg_EC_foam4(:,13);

F0_M3 = all_data_trialavg_EC_foam0(:,15);
F1_M3 = all_data_trialavg_EC_foam1(:,15);
F2_M3 = all_data_trialavg_EC_foam2(:,15);
F3_M3 = all_data_trialavg_EC_foam3(:,15);
F4_M3 = all_data_trialavg_EC_foam4(:,15);

W = table(categorical([0 0 0 1 1 1 2 2 2 3 3 3 4 4 4].'),categorical([1 2 3 1
2 3 1 2 3 1 2 3 1 2 3].'),'VariableNames',{'Foam','Meas'});

ML_RMS_tbl =
table(F0_M1,F0_M2,F0_M3,F1_M1,F1_M2,F1_M3,F2_M1,F2_M2,F2_M3,F3_M1,F3_M2,F3_M3
,F4_M1,F4_M2,F4_M3,'VariableNames',{'F0_M1','F0_M2','F0_M3','F1_M1','F1_M2','
F1_M3','F2_M1','F2_M2','F2_M3','F3_M1','F3_M2','F3_M3','F4_M1','F4_M2','F4_M3
'});

ML_RMS_rm = fitrm(ML_RMS_tbl,'F4_M3-F0_M1 ~ 1','WithinDesign',W);
[p1,ranovatbl_ML_RMS_stats] = ranova(ML_RMS_rm,'withinmodel','Foam*Meas');
results_ML_RMS=multcompare(ML_RMS_rm,'Meas','By','Foam');

%% AP Range
F0_M1 = all_data_trialavg_EC_foam0(:,16);
F1_M1 = all_data_trialavg_EC_foam1(:,16);
F2_M1 = all_data_trialavg_EC_foam2(:,16);
F3_M1 = all_data_trialavg_EC_foam3(:,16);
F4_M1 = all_data_trialavg_EC_foam4(:,16);

F0_M2 = all_data_trialavg_EC_foam0(:,18);
F1_M2 = all_data_trialavg_EC_foam1(:,18);
F2_M2 = all_data_trialavg_EC_foam2(:,18);
F3_M2 = all_data_trialavg_EC_foam3(:,18);
F4_M2 = all_data_trialavg_EC_foam4(:,18);

F0_M3 = all_data_trialavg_EC_foam0(:,20);
F1_M3 = all_data_trialavg_EC_foam1(:,20);
F2_M3 = all_data_trialavg_EC_foam2(:,20);
F3_M3 = all_data_trialavg_EC_foam3(:,20);
F4_M3 = all_data_trialavg_EC_foam4(:,20);

W = table(categorical([0 0 0 1 1 1 2 2 2 3 3 3 4 4 4].'),categorical([1 2 3 1
2 3 1 2 3 1 2 3 1 2 3].'),'VariableNames',{'Foam','Meas'});

AP_Ra_tbl =
table(F0_M1,F0_M2,F0_M3,F1_M1,F1_M2,F1_M3,F2_M1,F2_M2,F2_M3,F3_M1,F3_M2,F3_M3
,F4_M1,F4_M2,F4_M3,'VariableNames',{'F0_M1','F0_M2','F0_M3','F1_M1','F1_M2','
```

```
F1_M3','F2_M1','F2_M2','F2_M3','F3_M1','F3_M2','F3_M3','F4_M1','F4_M2','F4_M3
'});

AP_Ra_rm = fitrm(AP_Ra_tbl,'F4_M3-F0_M1 ~ 1','WithinDesign',W);
[p1,ranovatbl_AP_Ra_stats] = ranova(AP_Ra_rm,'withinmodel','Foam*Meas');
results_AP_Ra=multcompare(AP_Ra_rm,'Meas','By','Foam');

%% ML Range
F0_M1 = all_data_trialavg_EC_foam0(:,17);
F1_M1 = all_data_trialavg_EC_foam1(:,17);
F2_M1 = all_data_trialavg_EC_foam2(:,17);
F3_M1 = all_data_trialavg_EC_foam3(:,17);
F4_M1 = all_data_trialavg_EC_foam4(:,17);

F0_M2 = all_data_trialavg_EC_foam0(:,19);
F1_M2 = all_data_trialavg_EC_foam1(:,19);
F2_M2 = all_data_trialavg_EC_foam2(:,19);
F3_M2 = all_data_trialavg_EC_foam3(:,19);
F4_M2 = all_data_trialavg_EC_foam4(:,19);

F0_M3 = all_data_trialavg_EC_foam0(:,21);
F1_M3 = all_data_trialavg_EC_foam1(:,21);
F2_M3 = all_data_trialavg_EC_foam2(:,21);
F3_M3 = all_data_trialavg_EC_foam3(:,21);
F4_M3 = all_data_trialavg_EC_foam4(:,21);

W = table(categorical([0 0 0 1 1 1 2 2 2 3 3 3 4 4 4].'),categorical([1 2 3 1
2 3 1 2 3 1 2 3 1 2 3].'),'VariableNames',{'Foam','Meas'});

ML_Ra_tbl =
table(F0_M1,F0_M2,F0_M3,F1_M1,F1_M2,F1_M3,F2_M1,F2_M2,F2_M3,F3_M1,F3_M2,F3_M3
,F4_M1,F4_M2,F4_M3,'VariableNames',{'F0_M1','F0_M2','F0_M3','F1_M1','F1_M2','
F1_M3','F2_M1','F2_M2','F2_M3','F3_M1','F3_M2','F3_M3','F4_M1','F4_M2','F4_M3
'});

ML_Ra_rm = fitrm(ML_Ra_tbl,'F4_M3-F0_M1 ~ 1','WithinDesign',W);
[p1,ranovatbl_ML_Ra_stats] = ranova(ML_Ra_rm,'withinmodel','Foam*Meas');
results_ML_Ra=multcompare(ML_Ra_rm,'Meas','By','Foam');

%% std devs
stddev0=std(all_data_trialavg_EC_foam0);
stddev1=std(all_data_trialavg_EC_foam1);
stddev2=std(all_data_trialavg_EC_foam2);
stddev3=std(all_data_trialavg_EC_foam3);
stddev4=std(all_data_trialavg_EC_foam4);

stddevs =
[stddev0(4:21);stddev1(4:21);stddev2(4:21);stddev3(4:21);stddev4(4:21)];
```

SA2 Main Analysis Code

```
%% Main_Sway_Analysis
% Written by Eryn Gerber (eryngerber@ku.edu)
% The University of Kansas - Biodynamics Lab
% Last updated 1/12/2022
%
% Purpose: This is the main script used to analyze the foam study data by
% calculating sample entropy and rms of COP, RM, and TR timeseries
clear; clc; close all;

% Sampling Parameters
fsample = 100; %[Hz] % Kai collected at 200Hz and already downsampled to 100)
fdown = 100; % The desired frequency (in Hz) after downsampling the data
trial_time = 20; %[s]
trial_dt = 1/fsample; %[s]
g = 9.80665; %[m/s^2]
trim = 204;


%% Establish the path to the data

path = '/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 2 -
Sensory Organization/Raw Data/S';

% Choose the conditions of the trial(s) to be analyzed
maxsubj = 1023;
maxfoam = 2; % foam or no foam
maxvision = 3; % EO, EC, VR
maxtrial = 3; % 3 trials per condition/subject
maxcondition = 6; % 6 conditions for SO test

%% Establish the path to the data

path = '/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 2 -
Sensory Organization/Raw Data/S';

% Initialize empty results matrices
all_data=zeros(6*23,21);
all_data_trialavg = zeros(23*6*3,20);
all_trials = [];
```

```
RM_timeseries=zeros(1795,3,2,6,23); % time, trial#, direction (1=AP, 2=ML),
condition, subject
TR_timeseries=zeros(1795,3,2,6,23);
COP_timeseries=zeros(1795,3,2,6,23);
stop=zeros(23,3,6);
all_Force = [];

j=1;
ii=0;
for subject = 1001:1023

    fprintf([datestr(clock,21) ' \n'])
    fprintf('subject %d\n',subject)

    % Initialize the count and set figure number to match subject number
    count = 0;
    zeromean = 0;

    for condition = 1:maxcondition
        fprintf('SO Condition %d\n',condition)
        for trial = 1:maxtrial
            fprintf('Trial %d\n',trial)
            ii=ii+1;
            % Define the file to be analyzed and read the data
            fname = [path int2str(subject) '/' int2str(condition) '-'
int2str(trial) '.txt'];
            data = dlmread(fname,',',1,0);

            if condition<4
                foam = 0; % no foam
            elseif condition>3
                foam = 1; % foam
            end

            if or(condition==1, condition==4)
                vision = 0; % eyes open
            elseif or(condition==2, condition==5)
                vision = 1; % eyes closed
            elseif or(condition==3, condition==6)
                vision = 2; % VR
            end


            % Apply a 15 Hz low-pass filter to the raw data
            order = 4; %fourth order filter
            cutoff_freq = 15; %cutoff frequency in Hz
            time = [0:trial_dt:trial_time-0.01]';
            force=Low_Pass_Filt(order,cutoff_freq,fsample,data);

            % Downsample to 50Hz
            ratio = fsample/fdown;
            force = downsample(force, ratio);
            time = downsample(time,ratio);

            force_bad = zeros(length(force),1);
```

```
            for i=1000:length(force)
                if force(i,3)<(force(i-1,3))-4*std(force(1:1400,3))
                force_bad(i)=NaN;
                end
                if force(i,3)>(force(i-1,3))+4*std(force(1:1400,3))
                force_bad(i)=NaN;
                end
            end

            bad=isnan(force_bad);
            bad_int=find(bad==1);
            if sum(bad)>0
                stop(subject-1000,trial,condition)=bad_int(1);
            end



            force_AP = force(1:1795,1)-mean(force(1:1795,1));
            force_ML = force(1:1795,2)-mean(force(1:1795,2));
            all_Force = [all_Force,force_AP,force_ML];

            % Calculate COPy (AP) and COPx (ML)
            [COP_ML,COP_AP] = COP(force);
            COP_AP=COP_AP-mean(COP_AP); % + = anterior
            COP_ML=COP_ML-mean(COP_ML); % + = subject's right

            all_trials = [all_trials,COP_AP,COP_ML];



[RM_AP,TR_AP,F_0_AP]=RamblingTrembling(force_AP,COP_AP,time,trim);
            RM_timeseries(1:length(RM_AP),trial,1,condition,subject)= RM_AP;
            TR_timeseries(1:length(TR_AP),trial,1,condition,subject)= TR_AP;
            First_F0_AP(ii)=F_0_AP(1)';


[RM_ML,TR_ML,F_0_ML]=RamblingTrembling(force_ML,COP_ML,time,trim);
            RM_timeseries(1:length(RM_ML),trial,2,condition,subject)= RM_ML;
            TR_timeseries(1:length(TR_ML),trial,2,condition,subject)= TR_ML;
            First_F0_ML(ii)=F_0_ML(1)';

            % Trim COP to match RM and TR AFTER calculation
            COP_AP=COP_AP(1:end-trim);
            COP_ML=COP_ML(1:end-trim);
            COP_timeseries(:,trial,1,condition,subject)=COP_AP;
            COP_timeseries(:,trial,2,condition,subject)=COP_ML;


            %% Sample Entropy Calculations
            m = 2;
            r = 0.09855;
            SampEn_COP_AP = SampEn_Opt(COP_AP,m,r);
            SampEn_COP_ML = SampEn_Opt(COP_ML,m,r);
            SampEn_RM_AP = SampEn_Opt(RM_AP,m,r);
```

```
            SampEn_RM_ML = SampEn_Opt(RM_ML,m,r);
            SampEn_TR_AP = SampEn_Opt(TR_AP,m,r);
            SampEn_TR_ML = SampEn_Opt(TR_ML,m,r);

            %% RMS Calculations
            RMS_COP_AP = rms(COP_AP)./10; %cm
            RMS_COP_ML = rms(COP_ML)./10;
            RMS_RM_AP = rms(RM_AP)./10;
            RMS_RM_ML = rms(RM_ML)./10;
            RMS_TR_AP = rms(TR_AP)./10;
            RMS_TR_ML = rms(TR_ML)./10;

            %% Range Calculations
            [Range_COP_AP,Range_COP_ML] = (COP_Range(COP_AP,COP_ML)); %cm
            [Range_RM_AP,Range_RM_ML] = (COP_Range(RM_AP,RM_ML)); %cm
            [Range_TR_AP,Range_TR_ML] = (COP_Range(TR_AP,TR_ML)); %cm

            %% Data Output
            all_data(ii,:) =
[subject,condition,trial,SampEn_COP_AP,SampEn_COP_ML,SampEn_RM_AP,SampEn_RM_M
L,SampEn_TR_AP,SampEn_TR_ML,RMS_COP_AP,RMS_COP_ML,RMS_RM_AP,RMS_RM_ML,RMS_TR_
AP,RMS_TR_ML,Range_COP_AP,Range_COP_ML,Range_RM_AP,Range_RM_ML,Range_TR_AP,Ra
nge_TR_ML];

        end

        all_data_trialavg(j,:) = [subject,condition,mean(all_data(ii-
2:ii,4:21))];
        all_data_trialstd(j,:) = [subject,condition,std(all_data(ii-
2:ii,4:21))];

        j=j+1;

    end
end
```

SA2 Statistical Analysis

```
%% Separate by Sensory Org Condition (1-6)
all_data_bycnd=sortrows(all_data_trialavg(1:138,:),2);
all_data_bycnd =
[all_data_bycnd;(all_data_trialavg_cnd3+all_data_trialavg_cnd6)/2;(all_data_t
rialavg_cnd2+all_data_trialavg_cnd5)/2];


all_data_trialavg_cnd1=all_data_bycnd(1:23,:);
all_data_trialavg_cnd2=all_data_bycnd(24:46,:);
all_data_trialavg_cnd3=all_data_bycnd(47:69,:);
all_data_trialavg_cnd4=all_data_bycnd(70:92,:);
all_data_trialavg_cnd5=all_data_bycnd(93:115,:);
all_data_trialavg_cnd6=all_data_bycnd(116:138,:);

all_data_trialavg_cnd36 = (all_data_trialavg_cnd3+all_data_trialavg_cnd6)/2;
all_data_trialavg_cnd25 = (all_data_trialavg_cnd2+all_data_trialavg_cnd5)/2;
%%
all_data_trialavg_cnd36_v_cnd25 =
all_data_trialavg_cnd36./all_data_trialavg_cnd25;
all_data_trialavg_cnd36_v_cnd25_abs = abs(1-all_data_trialavg_cnd36_v_cnd25);

%% Compare 3+6 versus 2+5
[h,p]=ttest2(all_data_trialavg_cnd36,all_data_trialavg_cnd25); % healthy
individuals able to distinguish incorrect cues - no sig differences

%% Compare RM vs TR

[h,p] = ttest2(all_data_trialavg_cnd36_v_cnd25(:,[4 7 10 13 16
19]),all_data_trialavg_cnd36_v_cnd25(:,[5 8 11 14 17 20]));
all_data_trialavg_cnd36_v_cnd25_RM =
mean(all_data_trialavg_cnd36_v_cnd25(:,[4 7 10 13 16 19]));
all_data_trialavg_cnd36_v_cnd25_RM_std =
std(all_data_trialavg_cnd36_v_cnd25(:,[4 7 10 13 16 19]));
all_data_trialavg_cnd36_v_cnd25_TR =
mean(all_data_trialavg_cnd36_v_cnd25(:,[5 8 11 14 17 20]));
all_data_trialavg_cnd36_v_cnd25_TR_std =
std(all_data_trialavg_cnd36_v_cnd25(:,[5 8 11 14 17 20]));

%% ANOVA ML SampEn
all_data_3625 =
[all_data_trialavg_cnd36(:,4)',all_data_trialavg_cnd36(:,5)',all_data_trialav
g_cnd25(:,4)',all_data_trialavg_cnd25(:,5)']';
g1 = [repmat({'36'},46,1);repmat({'25'},46,1)];
g2 =
[repmat({'RM'},23,1);repmat({'TR'},23,1);repmat({'RM'},23,1);repmat({'TR'},23
,1)];
[p,tbl1,stats] = anovan(all_data_3625,{g1,g2},'model','interaction');

%% ANOVA AP SampEn
all_data_3625 =
[all_data_trialavg_cnd36(:,7)',all_data_trialavg_cnd36(:,8)',all_data_trialav
g_cnd25(:,7)',all_data_trialavg_cnd25(:,8)']';
g1 = [repmat({'36'},46,1);repmat({'25'},46,1)];
```

```
g2 =
[repmat({'RM'},23,1);repmat({'TR'},23,1);repmat({'RM'},23,1);repmat({'TR'},23
,1)];
[p,tbl2,stats] = anovan(all_data_3625,{g1,g2},'model','interaction');

%% ANOVA ML RMS
all_data_3625 =
[all_data_trialavg_cnd36(:,10)',all_data_trialavg_cnd36(:,11)',all_data_trial
avg_cnd25(:,10)',all_data_trialavg_cnd25(:,11)'];
g1 = [repmat({'36'},46,1);repmat({'25'},46,1)];
g2 =
[repmat({'RM'},23,1);repmat({'TR'},23,1);repmat({'RM'},23,1);repmat({'TR'},23
,1)];
[p,tbl3,stats] = anovan(all_data_3625,{g1,g2},'model','interaction');

%% ANOVA AP RMS
all_data_3625 =
[all_data_trialavg_cnd36(:,13)',all_data_trialavg_cnd36(:,14)',all_data_trial
avg_cnd25(:,13)',all_data_trialavg_cnd25(:,14)'];
g1 = [repmat({'36'},46,1);repmat({'25'},46,1)];
g2 =
[repmat({'RM'},23,1);repmat({'TR'},23,1);repmat({'RM'},23,1);repmat({'TR'},23
,1)];
[p,tbl4,stats] = anovan(all_data_3625,{g1,g2},'model','interaction');

%% ANOVA ML Range
all_data_3625 =
[all_data_trialavg_cnd36(:,16)',all_data_trialavg_cnd36(:,17)',all_data_trial
avg_cnd25(:,16)',all_data_trialavg_cnd25(:,17)'];
g1 = [repmat({'36'},46,1);repmat({'25'},46,1)];
g2 =
[repmat({'RM'},23,1);repmat({'TR'},23,1);repmat({'RM'},23,1);repmat({'TR'},23
,1)];
[p,tbl5,stats] = anovan(all_data_3625,{g1,g2},'model','interaction');

%% ANOVA AP Range
all_data_3625 =
[all_data_trialavg_cnd36(:,19)',all_data_trialavg_cnd36(:,20)',all_data_trial
avg_cnd25(:,19)',all_data_trialavg_cnd25(:,20)'];
g1 = [repmat({'36'},46,1);repmat({'25'},46,1)];
g2 =
[repmat({'RM'},23,1);repmat({'TR'},23,1);repmat({'RM'},23,1);repmat({'TR'},23
,1)];
[p,tbl6,stats] = anovan(all_data_3625,{g1,g2},'model','interaction');
%% Separate by Measure type, organize into ANOVA analysis groups
% Column key:
% 3 - ML COP SampEn
% 4 - AP COP SampEn
% 5 - ML RM SampEn
% 6 - AP RM SampEn
% 7 - ML TR SampEn
% 8 - AP TR SampEn
% 9 - ML COP RMS
% 10 - AP COP RMS
% 11 - ML RM RMS
% 12 - AP RM RMS
```

```
% 13 - ML TR RMS
% 14 - AP TR RMS
% 15 - ML COP Range
% 16 - AP COP Range
% 17 - ML RM Range
% 18 - AP RM Range
% 19 - ML TR Range
% 20 - AP TR Range

cnd = string(all_data_bycnd(:,2));
cnd_rep = repmat(all_data_bycnd(:,2),3,1);
COP_rep = repmat({'COP'},138,1);
RM_rep = repmat({'RM'},138,1);
TR_rep = repmat({'TR'},138,1);
meas_rep = [COP_rep;RM_rep;TR_rep];

% AP SampEn
AP_SE_all=all_data_bycnd(:,[2,3,5,7]);
AP_SE_all_vert =
[all_data_bycnd(:,3);all_data_bycnd(:,5);all_data_bycnd(:,7)];
% ML SampEn
ML_SE_all=all_data_bycnd(:,[2,4,6,8]);
ML_SE_all_vert =
[all_data_bycnd(:,4);all_data_bycnd(:,6);all_data_bycnd(:,8)];

% AP RMS
AP_RMS_all=all_data_bycnd(:,[2,9,11,13]);
AP_RMS_all_vert =
[all_data_bycnd(:,9);all_data_bycnd(:,11);all_data_bycnd(:,13)];
% ML RMS
ML_RMS_all=all_data_bycnd(:,[2,10,12,14]);
ML_RMS_all_vert =
[all_data_bycnd(:,10);all_data_bycnd(:,12);all_data_bycnd(:,14)];

% AP Range
AP_Ra_all=all_data_bycnd(:,[2,15,17,19]);
AP_Ra_all_vert =
[all_data_bycnd(:,15);all_data_bycnd(:,17);all_data_bycnd(:,19)];
% ML Range
ML_Ra_all=all_data_bycnd(:,[2,16,18,20]);
ML_Ra_all_vert =
[all_data_bycnd(:,16);all_data_bycnd(:,18);all_data_bycnd(:,20)];


%% AP SampEn
t =
table(cnd,AP_SE_all(:,2),AP_SE_all(:,3),AP_SE_all(:,4),'VariableNames',{'cnd'
,'COP','RM','TR'});
meas = table([1 2 3]','VariableNames',{'MeasureTypes'});
rm = fitrm(t,'COP-TR~cnd','WithinDesign',meas);
ranovatbl = ranova(rm);

results_AP_SE_bycnd=multcompare(rm,'MeasureTypes','By','cnd');
results_AP_SE_bymeas=multcompare(rm,'cnd','By','MeasureTypes');
%% ML SampEn
```

```
t =
table(cnd,ML_SE_all(:,2),ML_SE_all(:,3),ML_SE_all(:,4),'VariableNames',{'cnd'
,'COP','RM','TR'});
meas = table([1 2 3]','VariableNames',{'MeasureTypes'});
rm = fitrm(t,'COP-TR~cnd','WithinDesign',meas);
ranovatbl = ranova(rm);

results_ML_SE_bycnd=multcompare(rm,'MeasureTypes','By','cnd');
results_ML_SE_bymeas=multcompare(rm,'cnd','By','MeasureTypes');

%% AP RMS
t =
table(cnd,AP_RMS_all(:,2),AP_RMS_all(:,3),AP_RMS_all(:,4),'VariableNames',{'c
nd','COP','RM','TR'});
meas = table([1 2 3]','VariableNames',{'MeasureTypes'});
rm = fitrm(t,'COP-TR~cnd','WithinDesign',meas);
ranovatbl = ranova(rm);

results_AP_RMS_bycnd=multcompare(rm,'MeasureTypes','By','cnd');
results_AP_RMS_bymeas=multcompare(rm,'cnd','By','MeasureTypes');
%% ML RMS
t =
table(cnd,ML_RMS_all(:,2),ML_RMS_all(:,3),ML_RMS_all(:,4),'VariableNames',{'c
nd','COP','RM','TR'});
meas = table([1 2 3]','VariableNames',{'MeasureTypes'});
rm = fitrm(t,'COP-TR~cnd','WithinDesign',meas);
ranovatbl = ranova(rm);

results_ML_RMS_bycnd=multcompare(rm,'MeasureTypes','By','cnd');
results_ML_RMS_bymeas=multcompare(rm,'cnd','By','MeasureTypes');

%% AP Range
t =
table(cnd,AP_Ra_all(:,2),AP_Ra_all(:,3),AP_Ra_all(:,4),'VariableNames',{'cnd'
,'COP','RM','TR'});
meas = table([1 2 3]','VariableNames',{'MeasureTypes'});
rm = fitrm(t,'COP-TR~cnd','WithinDesign',meas);
ranovatbl = ranova(rm);

results_AP_Ra_bycnd=multcompare(rm,'MeasureTypes','By','cnd');
results_AP_Ra_bymeas=multcompare(rm,'cnd','By','MeasureTypes');
%% ML Range
t =
table(cnd,ML_Ra_all(:,2),ML_Ra_all(:,3),ML_Ra_all(:,4),'VariableNames',{'cnd'
,'COP','RM','TR'});
meas = table([1 2 3]','VariableNames',{'MeasureTypes'});
rm = fitrm(t,'COP-TR~cnd','WithinDesign',meas);
ranovatbl = ranova(rm);

results_ML_Ra_bycnd=multcompare(rm,'MeasureTypes','By','cnd');
results_ML_Ra_bymeas=multcompare(rm,'cnd','By','MeasureTypes');
```

SA3 Main Analysis Code

```
clear all;close all;
% Sampling Parameters
fsample = 2500; %[Hz]
fdown = 100; % The desired frequency (in Hz) after downsampling the data
trial_time = 90; %[s]
trial_dt = 1/fsample; %[s]
g = 9.80665; %[m/s^2]
trim_range1 = 20:9081;
trim_range2 = 50:9049;


%% Establish the path to the data

path = '/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 2 -
Sensory Organization/Raw Data/s';

% Choose the conditions of the trial(s) to be analyzed
maxsubj = 1010;
maxtrial = 2; % 2 trials: pre-vibe and during

% Initialize empty arrays
COP_timeseries=zeros(9000,2,2,10); % time, trials, AP or ML, subjects
RM_timeseries=zeros(9000,2,2,10);
TR_timeseries=zeros(9000,2,2,10);
all_data=zeros(20,20);

%% Establish the path to the data

path = '/Users/eryngerber/Documents/Biodynamics Lab/PhD Dissertation/SA 3 -
Vibrotactile/Raw Data/s';

all_Force = [];

ii=0;
for subject = 1001:1010

    fprintf([datestr(clock,21) ' \n'])
    fprintf('subject %d\n',subject)

    % Initialize the count and set figure number to match subject number


    colorstr='WH'; % analyzing white noise only


        %if subject==1007
```

```
        %else
        % Read the zeros file and calculate the mean for each channel
        zeromean = mean(dlmread([path int2str(subject) '/s' int2str(subject)
'_' colorstr '_zeros3.txt'],'\t',1,0));


        for trial = 1:maxtrial
            if trial==1
                trialstr='BL_EC_MAT_sway';
            elseif trial==2
                trialstr='STIM_EC_sway';
            end

            ii=ii+1;

            fprintf('Trial %d\n',trial)
%             ii=ii+1;
            % Define the file to be analyzed and read the data
            fname = [path int2str(subject) '/s' int2str(subject) '_' colorstr
'_' trialstr '.txt'];
            data = dlmread(fname,'\t',1,0);

            % Apply a 10 Hz low-pass filter to the raw data
            order = 4; %fourth order filter
            cutoff_freq = 10; %cutoff frequency in Hz
            force=Low_Pass_Filt(order,cutoff_freq,fsample,data(:,2:7));
            time = data(:,1);

            % Downsample
            ratio = fsample/fdown;
            force = downsample(force, ratio);
            time = downsample(time,ratio);
            time=time(trim_range1);

            force=V2f_fp4033(force,zeromean(:,13:18),1000);

            force_AP = force(trim_range1,1)-mean(force(trim_range1,1));
            force_ML = force(trim_range1,2)-mean(force(trim_range1,2));
            force_vert=force(trim_range1,3);

            % Calculate COPy (AP) and COPx (ML)
            [COP_AP,COP_ML] = COP(force(trim_range1,:));

            [RM_AP,TR_AP,F_0_AP]=RamblingTrembling(force_AP,COP_AP,time);
            RM_AP=RM_AP(trim_range2);
            RM_timeseries(:,trial,1,subject)= RM_AP;
            TR_AP=TR_AP(trim_range2);
            TR_timeseries(:,trial,1,subject)= TR_AP;

            [RM_ML,TR_ML,F_0_ML]=RamblingTrembling(force_ML,COP_ML,time);
            RM_ML=RM_ML(trim_range2);
            RM_timeseries(:,trial,2,subject)= RM_ML;
            TR_ML=TR_ML(trim_range2);
            TR_timeseries(:,trial,2,subject)= TR_ML;
```

```
            COP_AP=COP_AP(trim_range2);
            COP_timeseries(:,trial,1,subject)=COP_AP;
            COP_ML=COP_ML(trim_range2);
            COP_timeseries(:,trial,2,subject)=COP_ML;

            time=time(trim_range2);

            %% COP Plotting
            figure(subject)
            subplot(1,2,trial)
            %plot(time,force_ML,time,force_AP,time,force_vert)
            plot(COP_ML-mean(COP_ML),COP_AP-mean(COP_AP))

                        %% Sample Entropy Calculations
            m = 2;
            r = 0.09855;
            SampEn_COP_AP = SampEn_Opt(COP_AP,m,r);
            SampEn_COP_ML = SampEn_Opt(COP_ML,m,r);
            SampEn_RM_AP = SampEn_Opt(RM_AP,m,r);
            SampEn_RM_ML = SampEn_Opt(RM_ML,m,r);
            SampEn_TR_AP = SampEn_Opt(TR_AP,m,r);
            SampEn_TR_ML = SampEn_Opt(TR_ML,m,r);

            %% RMS Calculations
            RMS_COP_AP = rms(COP_AP)./10; %cm
            RMS_COP_ML = rms(COP_ML)./10;
            RMS_RM_AP = rms(RM_AP)./10;
            RMS_RM_ML = rms(RM_ML)./10;
            RMS_TR_AP = rms(TR_AP)./10;
            RMS_TR_ML = rms(TR_ML)./10;

            %% Range Calculations
            [Range_COP_AP,Range_COP_ML] = (COP_Range(COP_AP,COP_ML)); %cm
            [Range_RM_AP,Range_RM_ML] = (COP_Range(RM_AP,RM_ML)); %cm
            [Range_TR_AP,Range_TR_ML] = (COP_Range(TR_AP,TR_ML)); %cm

            %% Data Output
            all_data(ii,:) =
[subject,trial,SampEn_COP_AP,SampEn_COP_ML,SampEn_RM_AP,SampEn_RM_ML,SampEn_T
R_AP,SampEn_TR_ML,RMS_COP_AP,RMS_COP_ML,RMS_RM_AP,RMS_RM_ML,RMS_TR_AP,RMS_TR_
ML,Range_COP_AP,Range_COP_ML,Range_RM_AP,Range_RM_ML,Range_TR_AP,Range_TR_ML]
;

        end

    end
```