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Standardizing and evaluating clinical practices in Podiatry : postural control and Gait

Carole Puil

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Postural control and Gait

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List of abbreviations

Center of Mass	CoM
Center of Pressure	CoP
Central Nervous System	CNS
Depron®	DEP
Eyes Closed	EC
Eyes Open	EO
Metatarsal Head	MH
Orthomic®	ORT
Plantar Quotient	PQ
Plastazote®	PLA
Rod and Frame Test	RFT
Romberg Quotient	RQ
Stimulation under the Left foot	StimL
Stimulation under the Right foot	StimR
Subjective Visual Vertical	SVV

Scientific Contributions

Journal Papers

- Carole Puil, Anne-Hélène Olivier, Gérard Mauvoisin, Arnel Crétual - Evaluation of thin foam pads effect on static balance in healthy adults - *Gait and Posture* (under review)

Oral presentations

- Puil, C., Olivier, A. H., & Crétual, A. (2020, September). Clinical evaluation of plantar exteroceptive inefficiency: normalization of Plantar quotient. In *ENPODHE 2020-European Network of Podiatry in Higher Education*.
- Puil, C. (octobre 2023) Evaluation d'une stimulation sur la posture : visuelle et podale. In *48^{ème} Entretien de podologie, FNP*

Poster presentation

- Puil, C., Le Targat, K., Le Pesquer, O., Crétual, A., & Olivier, A. H. (2023, July). Effect of visual and foot measurement conditions on balance control variables in healthy adults. In *ISPGR 2023-Congres on International Society of Posture & Gait Research*.
- Puil, C., Crétual, A., & Olivier, A. H. (2022, July). Postural static task on a thin foam pad: evaluation of the plantar cutaneous system. In *ISPGR 2022-Congres on International Society of Posture & Gait Research*.
- Puil, C., Crétual, A., & Olivier, A. H. (2019). Impact of a thin plantar orthopedic insert on posture and locomotion. *Neurophysiologie Clinique*, 49(6), 454.

General introduction

The foot is a complex structure composed of 26 bones, 32 muscles, and more than 20 tendons, all organized into 33 joints. Surrounding this intricate system is the skin, which plays a vital role in protecting the underlying structures and conveying sensory information to the central nervous system (Drake et al., 2005) (Figure 1).

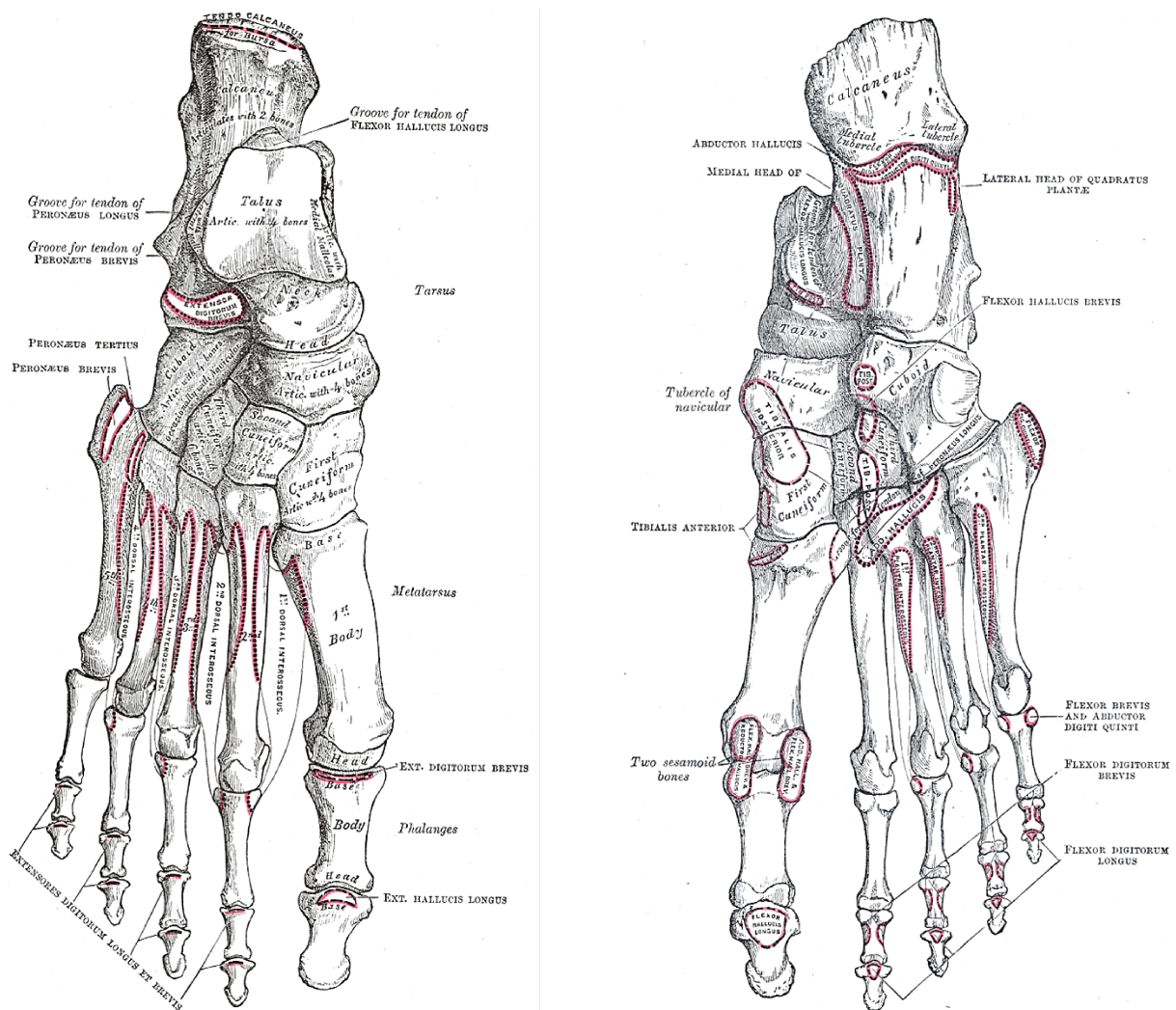


Figure 1: Bones and muscles insertions of the human foot (dorsal surface (left) and plantar surface (right)). Henry Vandyke Carter, Public domain, via Wikimedia Commons

The foot is the subject of study and intervention by podiatrists. Podiatry is a paramedical specialty in France that focuses on diagnosing, treating, and preventing issues related to the feet, ankles, and

lower extremities. Podiatrists are skilled in managing musculoskeletal disorders that can affect posture, balance, locomotion. Their expertise, which is regulated by several laws in France (Law 2023-379, law 2020-475, law 2019-774 article 27, Law 2009-956) (Journal officiel, n.d.), lies therefore in evaluating these functions through plantar analysis (Bonanno et al., 2017; Spink et al., 2011). Additionally, they are well-equipped to handle various foot-related conditions such as pain, injuries, deformities, and infections. Podiatrists can also provide orthotic devices, prescribe medications, and offer advice on proper foot care and suitable footwear. With their expertise, they contribute to improving the patient's mobility, have a significant impact on overall musculoskeletal health and posture, and overall quality of life. Collaborating with other healthcare professionals, such as physical therapists and orthopedic specialists, can further enhance the comprehensive care provided to patients with complex musculoskeletal conditions (Law 2023-379, law 2020-475, law 2019-774 article 27, Law 2009-956) (Journal officiel, n.d.)

Evaluation is then a fundamental aspect of podiatrists' tasks. Several tools and assessments are classically used (Harrison-Blount et al., 2019):

- Patient history: allows gathering a detailed medical history, including any relevant past foot injuries, medical conditions, or surgeries (Woodburn & Sutcliffe, 1996).
- Physical examination: a comprehensive examination of the feet, ankles, and lower limbs is conducted to check for signs of inflammation, deformities, and overall foot structure (Wrobel & Armstrong, 2008). The height and structure of the foot arches are assessed to detect conditions such as flat feet (pes planus) or high arches (pes cavus).
- Footwear assessment: The type and condition of the patient's footwear are evaluated to identify any issues that may contribute to foot problems (Barton et al., 2009).
- Range of motion (ROM): the ROM in the foot and ankle joints is evaluated to detect any limitations or abnormalities (Martin & McPoil, 2005).
- Muscle strength and flexibility: the strength and flexibility of the muscles surrounding the foot and ankle are evaluated to identify any weaknesses (Liebermann & Katz, 2003).
- Foot posture assessment: both the static and dynamic postures of the foot are evaluated with tests such as Foot Posture Index to identify pronation or supination tendencies and any abnormalities (Redmond et al., 2008).
- Kinematics of gait: the podiatrist focuses on the patient's gait during walking to understand how the foot functions and to identify any abnormalities. This analysis may involve visually observing the gait or using specialized equipment such as gait analysis systems, force platforms or pressure platforms (Barnett, 1998). This provides insights into areas of excessive pressure or abnormal weight distribution, but also abnormal gait patterns.
- Static balance assessment: the podiatrist evaluates the patient's static balance. This analysis may involve force platform or pressure platform (Najafi et al., 2013).

The sensory function of the foot is well documented as its informational role (Tresilian, 2012). Collectively, the information sent by the feet to the brain contributes to overall proprioception and body awareness. Good communication between the feet and the central nervous system is crucial for balanced gait, proper posture, and harmonious coordination of movements. Hence, the informational role of the foot is of crucial importance in our daily life and physical activities (Shumway-Cook & Woollacott, 2007). There are several ways to evaluate the sensory capacity of

the foot. Sensory tests are commonly used by healthcare professionals such as podiatrists, neurologists, and physiotherapists to assess the tactile and proprioceptive sensitivity of the foot.

Here are some key aspects of its role and its evaluation:

- Somatosensory role: the foot is covered with an abundance of sensory nerve endings that are highly sensitive to touch, but also pain receptors. As we walk or encounter different surfaces, these receptors send crucial information to the brain regarding texture, temperature, pressure on the skin, pain or vibration (K. Johnson, 2001). This sensory information helps us to navigate and interact with our environment. Various tests can assess the foot ability to perceive that information. This may include Semmes-Weinstein monofilaments to test the ability to detect light touch at different areas of the foot (Feng et al., 2009). Tactile Discrimination Tests assess the foot ability to discriminate between different textures and shapes (Lundborg & Rosén, 2004). Vibratory Sensation Testing evaluate the foot ability to detect vibrations, which is crucial for sensory feedback during movement. Sensory Nerve Function Testing assesses the integrity and function of the sensory nerves in the foot. Pain-sensitive nerve endings in the foot signals the presence of painful stimuli, such as injuries or inflammation. This sensation of pain is a protective reaction that alerts us to potential harm to the foot.
- Proprioception: proprioception is the body ability to perceive its position in space without having to look at it. The feet are rich in proprioceptive receptors that inform the brain about the position, orientation, and movement of the feet and ankles (Dietz, 2002). This helps maintain balance and coordinate body movements. Proprioception tests evaluate the foot capacity to perceive its position and movements without visual input (tests of ankle joint position sense, toe orientation, and joint awareness during balance tasks).
- Postural Feedback: the foot provides important information about postural balance. When we are standing or moving, information from the feet allows the brain to regulate posture and constantly readjust the body's position to avoid falls or imbalance. It can detect irregularities in the ground, variations in surface, and changes in terrain. This information helps adjust gait and react appropriately to different ground conditions. Several assessments can provide insight of the foot capacity: balance assessments help determine how well the foot contributes to maintaining stability and posture (balance tasks on different surfaces) (Preszner-Domjan et al., 2012), evaluation of the foot role in gait can provide insights into how the foot interacts with the ground, and how it adapts to changes in the walking surface (or orthopedic devices) and foot pressure analysis shows how pressure is distributed across the foot during standing and walking.

One of the clinically used tools is the foam pad to assess the patient's balance control (Figure 2). The foam pad is made of an unstable and padded surface designed to create an unstable environment under the feet and challenge patient balance control. This assesses the ability to maintain balance under static conditions and is analyzed with a force platform recording the Center of Pressure (CoP) movement (Patel et al., 2008). This assessment is especially useful in identifying any balance issues or proprioceptive deficits that may be related to the foot sensory capacity.

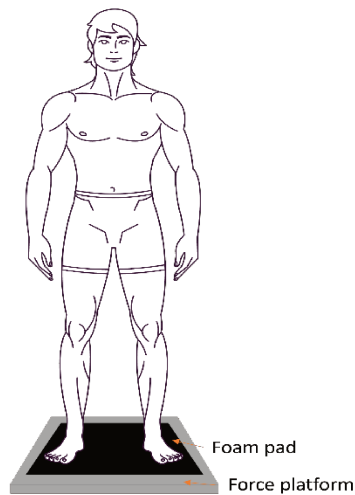


Figure 2: Static position on foam pad in between the feet and the force platform

Static balance refers to the ability to maintain stability and control while in a stationary position such as standing (Shumway-Cook & Woollacott, 2007). Dynamic balance, on the other hand, is the ability to maintain stability and control during movement or locomotion, such as walking, running, or jumping (Rosenbaum, 2009). Unlike static balance, dynamic balance requires continuous adjustments in response to changing conditions, such as shifts in weight distribution and variations in terrain. The link between static balance and dynamic balance lies in their interdependence. Static balance provides the foundation for dynamic balance. Proper alignment and control in a static position are essential for initiating and sustaining controlled movements during locomotion. During walking, the body's center of mass is continually shifting and transitioning from one foot to the other. This requires a well-developed static balance to execute smooth and coordinated movements without compromising stability (Lajoie et al., 1993). The sensory inputs utilized for static balance are crucial during locomotion, where they continuously inform the brain about the body's position, movement, and interaction with the environment. As static balance and dynamic balance are complementary components of postural control, the deficit of one can influence the effectiveness of the other, and both are vital for maintaining stability and efficient locomotion. To gain a comprehensive understanding of podal sensory integration during locomotion, it is essential to incorporate gait analysis which can provide more accurate information about the foot interaction with the ground, weight distribution, and proprioceptive responses during walking (Robb & Perry, 2022). While static tasks can provide useful information about static balance and sensory integration, they may not fully represent a person's dynamic podal sensory integration during locomotion. Both static and dynamic task should then be considered when evaluating foot function.

By combining static and dynamic evaluations, healthcare professionals can gain a more comprehensive view of a person's podal sensory integration and its impact on balance and stability during different activities. This allows for the identification of potential dynamic imbalances or locomotion-specific issues and enables more tailored and targeted interventions especially on orthotics devices.

As our understanding of healthcare advances, the importance of evidence-based practice becomes a priority. It is essential to adopt an evidence-based approach to care, which involves utilizing the latest scientific literature, the patient's preferences, and the clinician's expertise to provide the best possible solutions. By integrating up-to-date scientific information into the diagnostic and treatment processes, healthcare professionals can ensure that their decisions are well-informed and based on the most current knowledge available. This approach not only enhances the quality of care but also promotes patient-centered treatment.

This thesis is deeply grounded in its clinical applications. The objectives of this research are to better understand plantar integration assessment and provide guidelines for clinicians to perform such an evaluation. This thesis is particularly interested in evaluations using foams. The first chapter presents the literature related to the topics addressed in this work. The second chapter aims to assess the evaluation of foot information on a static task. As no gold standard evaluation of its function exist, it is necessary to understand and make norms of the impact of the visio-podal information. The third chapter aims at assessing the podiatrist intervention in static and in dynamic with the example of an orthopedic insole.

Chapter 1: State of the Art

A. Motor control and balance control

Motor control includes complex processes and mechanisms to plan, execute, and coordinate movements. These movements can range from simple actions such as walking to complex activities such as playing drums or performing gymnastics. Motor control involves various sensory, neural, and muscular components working together to achieve precise and purposeful motion. It includes both central (CNS) and peripheral (muscles, nerves, and receptors) contributions. The CNS generates motor commands, while the peripheral components carry out those commands through muscle contractions (Rosenbaum, 2009).

Several motor control theories have been proposed to explain how the CNS plans, executes, and coordinates movements. Those theories have been reviewed by Shumway Cook (Shumway-Cook & Woollacott, 2007) and help us understanding the underlying mechanisms and processes involved in human motor behavior. We can first refer to the **internal model theory** which is based on feedforward control, where the CNS anticipates the consequences of movements and adjusts them in advance (Francis & Wonham, 1976). The CNS creates internal models of the body, its dynamics, and the environment which are used to predict the outcomes of motor commands before they are executed. It is linked to the **optimal control theory** which provides mathematical solutions to describe the generation of movement in order to realize specific goals. Movements are planned to minimize or maximize certain criteria, such as the amount of energy utilized or task precision (Kleinman et al., 1970). It considers movements as solutions to optimization problems. In the same way, **the task-dynamic theory** explains the role of task-specific goals in guiding motor control. Movements are organized around the task's requirements, and the CNS adjusts muscle activations to achieve the desired task outcome. It highlights the importance of the interaction between the task and the CNS in movement generation. **The hierarchical theory** which is based on a top-down control with an interaction between different levels of the CNS (Latash et al., 2010) (Figure 3). It implies that the CNS organizes movement control in a hierarchical manner. It proposes that higher brain centers, such as the cerebral cortex, plan and initiate movements, while lower centers, such as the spinal cord, execute the movements. **The motor programming theory** refers to the processes by which the brain organizes and plants motor skills and movement. This involves the cognitive processes that occur before the initiation of a motor action. It includes tasks like selecting the appropriate motor program, setting the parameters for the movement, and organizing the sequence of muscle activations. The theory also considers how the CNS uses sensory feedback, such as proprioception (awareness of body position) and vision, to monitor the ongoing movement and make adjustments if errors occur, and it suggests that the CNS stores motor programs for frequently used actions, making it easier to perform them

in the future without needing to re-plan the entire movement from scratch (Latash et al., 2010). **The motor schema theory** is linked to the motor programming theory (R. A. Schmidt et al., 2018) (Figure 4). These theories help explain how movements can be adapted to different situations while maintaining their essential characteristics and how complex movements can be performed with relative ease and efficiency (Summers & Anson, 2009). They suggest that CNS stores general schemas for producing movements. These schemas are learned through experience and guide the selection and modification of motor commands to achieve goal movements. To initiate a movement, the appropriate motor program is selected and executed. In the dynamic systems theory, motor control is considered as a result of interactions between various factors, such as the environment, the musculoskeletal system, and the CNS (Davids et al., 2003). Movements emerge from the self-organization of these interacting components. This theory highlighted the adaptability and flexibility of movement patterns to changing conditions. Equilibrium Point Hypothesis is based on the fact that the CNS controls movement by modulating the activation levels of muscles around specific joint equilibrium points. These equilibrium points correspond to stable configurations of the musculoskeletal system. The CNS adjusts muscle activations to move between these equilibrium points and generate coordinated movements (Feldman, 1986; Feldman & Levin, 2009). Both theories acknowledge that complex interactions between muscle systems and nervous system lead to adaptive motor behaviors.

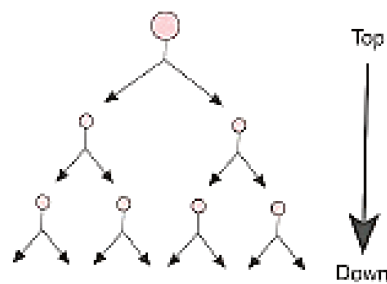


Figure 3: The hierarchical control model is characterized by a top-down structure, in which higher centers are always in charge of lower centers (Shumway-Cook, Woollacott, 2007)

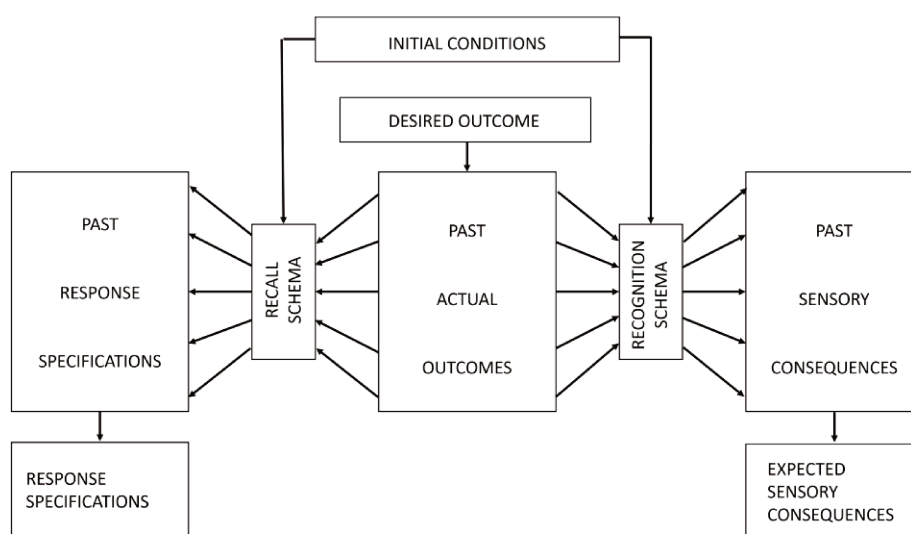


Figure 4: Schmidt's schema theory of motor learning (Schmidt, 2018)

These theories provide different perspectives on how the CNS controls movement, and many of them are not mutually exclusive. One of the keys to an efficient movement is stability. Indeed, motor control and balance control are fundamentally rooted in the intricate relationship between movement and stability. Balance control is a specialized aspect of motor control that focuses on maintaining equilibrium and stability during various activities (Winter et al., 1990). Those two concepts are closely linked both in static and dynamic. On one hand, equilibrium is a state in which forces and torques balance out, resulting in no net acceleration. Stability, on the other hand, is a measure of how well an object or system can return to equilibrium after being disturbed.

As motor control, balance control relies on sensory input from the vestibular system, visual system and somatosensory system. They provide information about body posture, motion and environment. Those information are used to generate motor commands that permit movement (L. M. Nashner, 1982) (Figure 5).

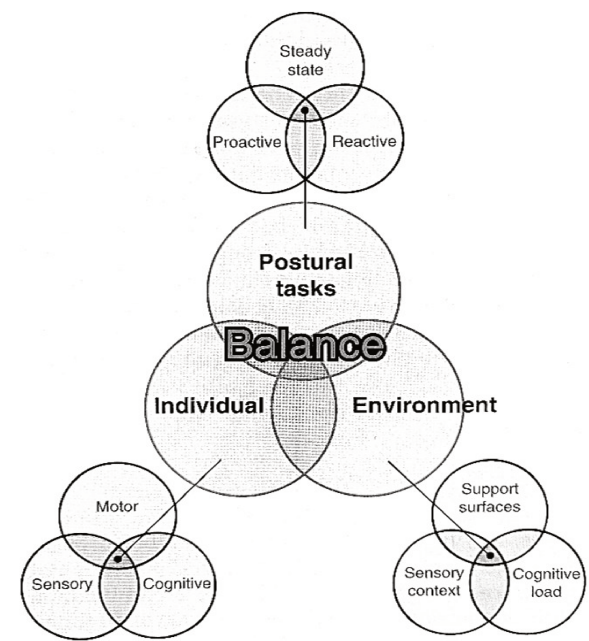


Figure 5: Systems model of Balance control (Shumway-Cook, Woollacott, 2007)

The sensory input integration uses information from the vestibular system in the inner ear by detecting changes in head position and motion (Peterka, 2018). The visual system provides information about the body's orientation and location of potential threats with respect to external environment landmarks. The somatosensory system includes receptors in the skin, muscles, tendons, and joints. It provides information about body position, movement, and forces acting on the body. Information from these sensory systems is transmitted to the brain via dedicated neural pathways. The vestibular information travels through the vestibulocochlear nerve, visual information through the optic nerve, and somatosensory information through various nerves associated with different body parts. The CNS processes the incoming sensory information in specialized areas, such as specific brain regions (cerebellum, brainstem nuclei and the somatosensory cortex). By integrating that information from different sources, the CNS creates a realistic image of the body motion and position in the surrounding environment. The CNS has a capacity of learning from experience and is able to compare the sensory input to the previous reference model of balance (Shumway-Cook & Woollacott, 2007; Tresilian, 2012). That is a more efficient way to react and anticipate balance challenges by learned strategies. That is called the

plasticity of the CNS. This learning process involves strengthening neural pathways and optimizing motor commands (Surgent et al., 2019; Winter et al., 1990). Based on the integrated sensory information and the comparison with the internal reference model, the CNS generates motor commands to activate muscles for balance adjustments. As muscles respond to the motor commands and make adjustments, sensory feedback is generated (Dietz, 2002). This feedback provides information about the effectiveness of the muscle contractions in maintaining balance. CNS continuously monitors this feedback and can adjust motor commands in real-time to ensure stability. Neural processing for balance control is highly adaptive. CNS constantly fine-tunes motor commands based on changing sensory input and feedback. For instance, when standing on an unstable surface, CNS might increase muscle activity and tension to counteract the instability. The same neural mechanisms that coordinate muscle activations for movements are engaged to stabilize the body during balance challenges with constantly ongoing minute adjustments in order to counteract perturbations and maintain stability. Muscles, especially those in the legs and trunk, play a crucial role in balance control (Laughton et al., 2003). Neural processing in balance control involves the intricate communication and integration of sensory information, neural pathways, and motor commands within the CNS (Figure 6). This communication and process are called multisensory integration (Barnett-Cowan & Harris, 2009; Bronstein, 2016). It is a neurological and cognitive process through which information from sensory modalities is combined and processed to form a unified perception or representation of the external world. This integration allows individuals to perceive and interact with their environment in a more comprehensive and accurate manner. As it involves the brain's ability to merge and combine information from different sensory sources, this integration results in enhanced perception and improved sensory processing compared to relying on a single sensory modality alone. This can lead to more accurate judgments and faster reaction times.

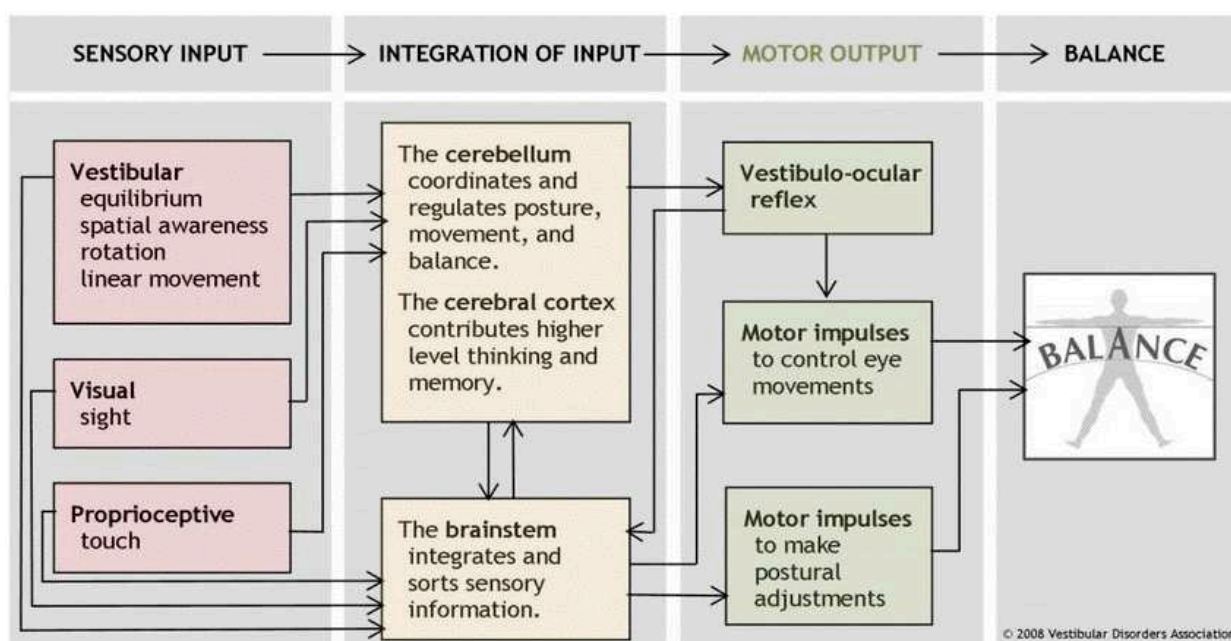


Figure 6: The human balance system (Courtesy of the Vestibular Disorders Association)

To better understand the impact of environment on static and dynamic balance, it is necessary to know the different systems of afferences and their role in those tasks.

B. Sensory Systems

B.1. Vestibular system

The vestibular system is essential for maintaining balance, coordinating movements, and perceiving the body's position in space in relation to gravity. It works in conjunction with other sensory systems to provide a comprehensive picture of the external world and the body's relationship to it.

1.1. Anatomy

The vestibular system is located within the inner ear and consists of the vestibular organs, which include the otolith organs (including utricle and saccule), and three semicircular canals (Goldberg, 2012; Tresilian, 2012) (Figure 7).

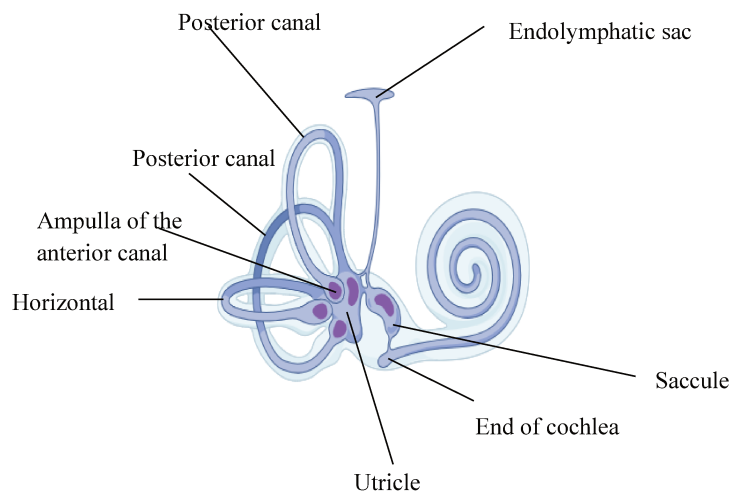


Figure 7: Vestibular apparatus (Created with BioRender.com)

a. Otolith organs

They are composed with the utricle and the saccule. These organs are essential components of the vestibular system.

Utricle

The utricle is a small, sac-like structure located within the vestibule of the inner ear. The vestibule is a central chamber that connects the cochlea (responsible for hearing) and the semicircular canals. The utricle is situated horizontally within the vestibule.

Saccule

The saccule is a small, sac-like structure situated within the vestibule of the inner ear, alongside the utricle. It is positioned vertically within the vestibule, perpendicular to the utricle.

Physiology and function

Inside both the utricle and the saccule, there are specialized sensory hair cells (called stereocilia) and a layer of jelly-like substance containing tiny crystals called otoliths or otoconia. These otoliths are made of calcium carbonate and provide weight to the utricle and the saccule. When the head moves or accelerates linearly, the otoliths move and stimulate the hair cells. The utricle primarily detects changes in linear acceleration and head movements in the horizontal plane (forward backward or side to side motions). The saccule detects changes in linear acceleration and head movements in the vertical plane (up-and-down motions or head tilts). Those movements make otoliths shift. It bends the hair cells creating electrical signals that are transmitted to the CNS. This information helps maintain balance and adjust muscle tension during movement (Angelaki & Cullen, 2008; Goldberg, 2012).

They contribute to maintaining balance and stability during movements. The utricle is involved in horizontal shifts and changes in head orientation parallel to the ground, while the saccule to vertical shifts and changes in head orientation perpendicular to the ground.

Due to their specialty, the utricle helps determine the body position in relation to the horizon while saccule to gravity. They participate to regulate postural adjustments to prevent falling.

The sensitivity of the utricle and saccule varies among individuals and can also be influenced by factors such as age, health conditions... (Paillard et al., 2013). They are capable of detecting very subtle accelerations, often in the range of $\mu\text{m}/\text{s}^2$ or even smaller. This very specific sensitivity allows them to perceive even minor changes in motion.

In a standing task, they help perceive the direction of gravity, allowing to maintain an upright posture. The stereocilia respond to the constant pull of gravity on the otoconia, providing information about the vertical orientation of the head (Cullen, 2012) (Figure 8).

In a locomotor task, they detect changes in linear acceleration. While doing forward and backward movement, as well as changes in direction, the stereocilia respond to these changes in motion. This information is integrated with input from other sensory systems such as vision and proprioception to help you maintain balance and adjust your movements accordingly (McFadyen, 2004).

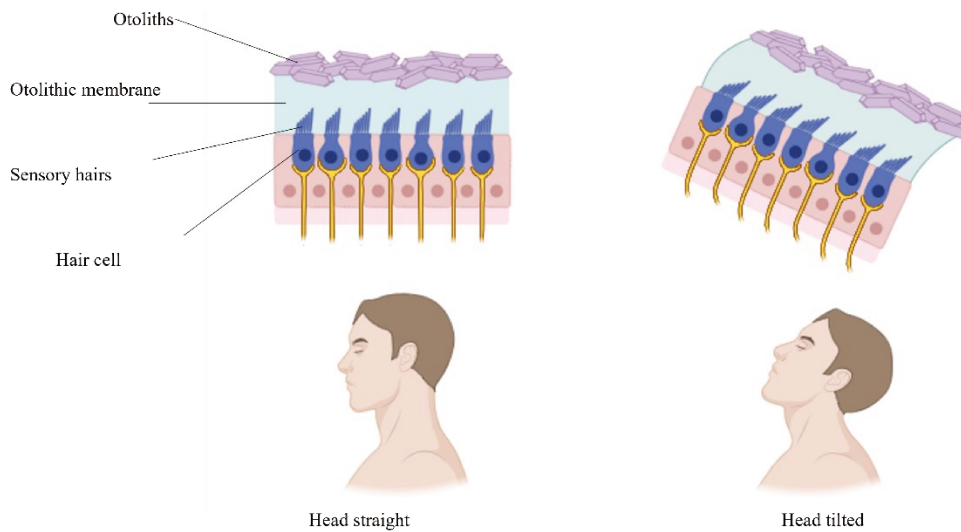


Figure 8: Otolith organs (created with www.BioRender.com)

b. Semicircular canals

The semicircular canals are another integral part of the inner ear vestibular system, alongside the otolith organs (Goldberg, 2012).

There are three semicircular canals in each ear, approximately orthogonal to each other. These canals are named the anterior (superior), posterior, and horizontal (lateral) canals. Each canal has a dilated end called the ampulla, which contains sensory structures known as the crista ampullaris. They are situated in three different planes to detect acceleration in various directions.

Physiology and function

The canals are filled with a fluid called endolymph with a composition different from the surrounding fluid, called perilymph.

When the head moves in different directions, the endolymph inside the semicircular canals lags behind due to inertia. This differential movement of the endolymph causes the cupula, a gelatinous structure with hair cells embedded in it, to deflect. Hair cells have tiny hair-like projections called stereocilia. The cupula extends across the width of the ampulla, where the canal dilates. This causes the hair cells within the crista ampullaris to bend. Bending of the stereocilia triggers a mechano-electrical transduction signal that is sent to the CNS through the vestibular nerve.

Each semicircular canal is specialized to detect rotations in a specific plane (Goldberg, 2012).

- Anterior (Superior) canal is oriented vertically and is primarily responsible for detecting changes in pitch, such as nodding the head up and down.
- Posterior canal is also oriented vertically and detects changes in pitch, but in the opposite direction from the anterior canal. It is responsible for movements like tilting the head backward and forward.
- Horizontal (lateral) canal is oriented horizontally and detects rotational movements in the horizontal plane.

Semicircular canals are responsible for detecting dynamic movements and changes in angular velocity rather than static tasks. However, they do indirectly contribute to maintaining static balance and posture through their interactions with the otolith organs.

In a static task, they contribute indirectly by influencing the overall vestibular system's input, which is integrated with visual and proprioceptive cues to ensure stability and proper orientation. During locomotion, they play a crucial role in helping to maintain balance and stabilize vision by detecting the rotational movements of your head that result from the natural swaying of your body during each step. These movements include subtle changes in yaw, pitch, and roll as your body shifts its weight. They help the CNS anticipate and adjust for these movements, allowing the balance to be maintained and a stable visual field while walking (Lindeman, 2013).

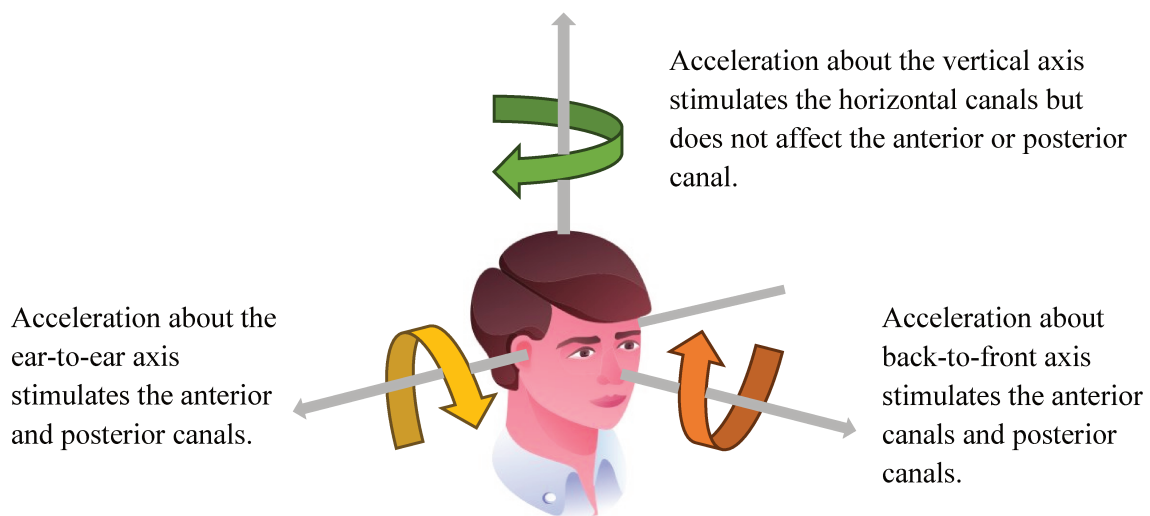


Figure 9: cardinal axis of head rotation (Tresilian, 2012)

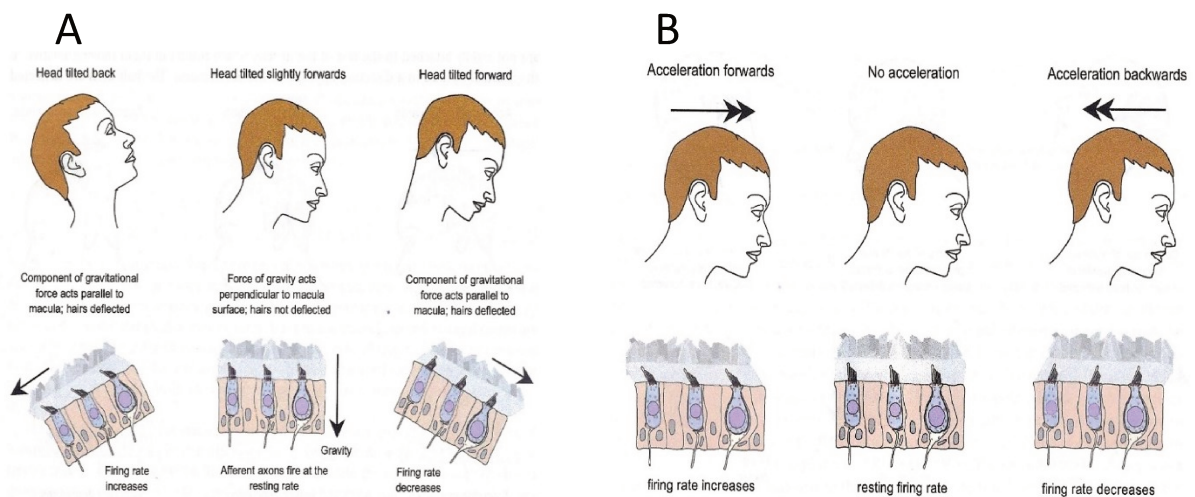


Figure 10: A: Effects of head tilt on the utricular maculae. B: Effects of translation acceleration of the head on the utricular maculae (Tresilian, 2012)

Finally, the vestibular system's ability to function as an inertial sensor stems from the combination of information derived from both the otolith organs and the semicircular canals. The otolith organs

primarily detect linear accelerations and the direction of gravity, whereas the semicircular canals focus on angular accelerations and rotational movements (Figure 9). The nonlinear interactions between these two sets of sensory inputs are essential for achieving accurate and precise sensory integration. By combining the two of them, the vestibular system effectively acts as an inertial sensor that aids in perceiving changes in motion, spatial orientation and awareness (Angelaki & Cullen, 2008) (Figure 10).

1.2. Evaluation

On one hand, the vestibular function can be medically assessed. On the other hand, several clinical tests exist, such as vestibular evoked myogenic potential test, earth-vertical axis rotational testing, caloric testing (van de Berg et al., 2018; Wuyts et al., 2007). To understand its role in the literature, researchers use pathological populations and compare them to physiological ones. Unlike the visual system, it is not possible to subject the vestibular system to different experimental conditions (FAAN & MD, 2010).

B.2. Visual system

The visual system refers to the complex network of structures and processes within the human body that allows the perception and interpretation of visual information from the environment. It includes eyes, neural pathways and the CNS regions responsible for processing and making sense of visual input.

2.1. Anatomy

The eyes are the primary sensory organs responsible for capturing light and converting it into neural signals. They enable us to perceive colors, shapes, depth, and motion, contributing to our rich visual experience (Prasad & Galetta, 2011).

The eye has multiple components (Remington & Goodwin, 2021) (Figure 11) :

- Cornea: it is a transparent outermost layer that is a protective barrier. It focuses incoming light into the lens.
- Lens: it is a flexible and transparent structure which is located behind the iris. It focuses the light going through the cornea to the retina. It is capable of focusing in order to better accommodate.
- Iris: this is the colored part of the eye. It controls the amount of light coming into the retina by adjusting the size of the pupil (in dark environment, it dilates, whereas in light environment, it reduces).
- Retina: it is a layer of neural tissue lining the back of the eye. Millions of photoreceptors (cells which convert light into electrical signals for the CNS) are covering it. In the middle of the retina, the fovea is responsible for central vision.
- Photoreceptors: there are 2 kinds of cells: rods and cones, that are detailed below.

- Optic nerve: it is composed of nerve fibers that connect the retina to the CNS. It transmits visual information to the CNS's visual processing centers.

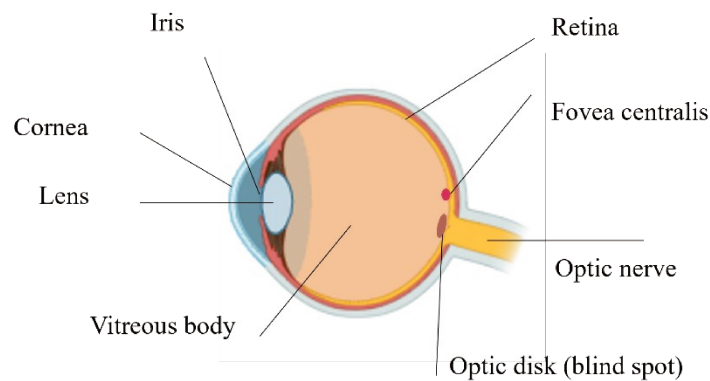


Figure 11: Eye anatomy (created using www.Biorender.com)

Rods (Figure 12)

Those photoreceptors are composed of 3 parts (Remington & Goodwin, 2021):

- Outer segment: it contains stacks of membranous discs that contain the light-sensitive pigment called rhodopsin. Rhodopsin plays a crucial role in the absorption of photons (particles of light) and the initiation of the visual signal.
- Inner segment: it contains the cellular machinery necessary for maintaining the rod cell's structure and function. It houses the organelles responsible for energy production and cellular processes.
- Cell body: it contains the nucleus and other essential cellular components.
- Synaptic Terminal: it is the end portion of the rod cell that forms synapses with other neurons in the retina.

Cones (Figure 12)

There are three main types of cone cells, each sensitive to a specific range of wavelengths of light (Bowmaker & Dartnall, 1980):

- S-Cones (Short-Wavelength): sensitive to short wavelengths of light, which correspond to blue colors. They are most responsive to light around the blue end of the spectrum.
- M-Cones (Medium-Wavelength): sensitive to medium wavelengths of light, primarily in the green part of the spectrum.
- L-Cones (Long-Wavelength): sensitive to long wavelengths of light, primarily in the red part of the spectrum.

Cones are composed of several structures (Remington & Goodwin, 2021):

- Outer segment: it contains stacks of membranous discs that house the light-sensitive pigments responsible for color vision.
- Inner segment: it contains the cellular machinery necessary for maintaining the cell's structure and function. It includes various organelles, such as mitochondria for energy production and other cellular components that support the cell metabolic activities.

- Cell body: it contains the nucleus, which contains the cell genetic material and controls its functions. The nucleus plays a crucial role in regulating the cell's activities and responds to incoming signals.
- Synaptic terminal: it is the end part of the cone cell that connects with other neurons in the retina.

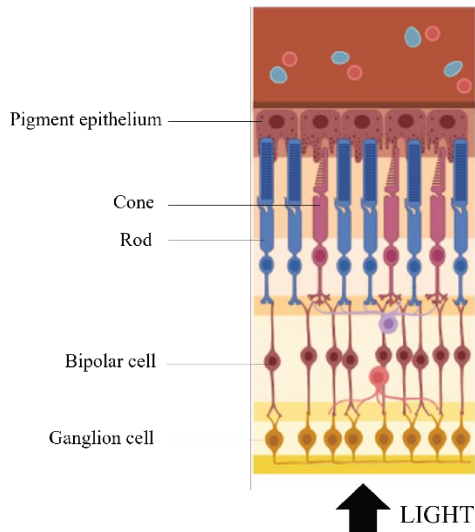


Figure 12: Photoreceptors (Rod and Cone) (created using www.Biorender.com)

For cones and rods, when light stimulates the cone cells, they generate electrical signals that are transmitted to neighboring retinal cells, such as bipolar cells and ganglion cells, through synapses. These signals are eventually transmitted along the optic nerve to CNS for processing.

The ventral and dorsal pathways are two distinct neural pathways in the visual system of the brain. They work in parallel and are interconnected integrating both objects and motion. The ventral pathway primarily processes information related to the identification and recognition of objects and their properties, such as color, shape, and texture. It plays a role in recognition, and interpretation of visual scenes (Kravitz et al., 2013). The dorsal pathway is processing information about the location, motion and special orientation of objects. It plays a role in guiding motor action, perceiving depth (Siegel et al., 2008).

Physiology and function

Rod cells are specialized for low-light vision. In fact, they excel in conditions, such as dimly lit environments or during nighttime. This type of vision is known as scotopic vision. Rods contain a light-sensitive pigment called rhodopsin that allows them to detect even small amounts of light. Rod cells are densely packed in the peripheral regions of the retina, particularly outside the fovea. This distribution allows a better peripheral vision in low-light situations. The high sensitivity of rods comes at a cost – they are less sensitive to fine details and do not provide high-resolution vision like cones. We rely on the rods for detecting overall shapes and movements. Rods contribute to our overall visual perception, but they do not provide the same level of visual acuity as cones.

They do not discriminate between different colors. Instead, they primarily provide information about light intensity, allowing us to perceive shades of gray in low-light conditions (Lamb, 2016).

The CNS processes the signals from cone cells to create the perception of color. When light enters the eye and stimulates cone cells, the different responses of these cones to various wavelengths allow us to perceive a wide range of colors. The combination of the signals from these cells produces the full spectrum of colors that we see.

Opposite to rod cells, cones are most active in well-lit conditions, known as photopic vision. They provide us with high-resolution color vision and allow us to discern fine details and differences in color. Cones are also responsible for visual acuity, which refers to the sharpness and clarity of the vision. Since cones are densely packed in the fovea, central vision is much more detailed and clear than peripheral vision (Lamb, 2016). Cones and rod cells work in conjunction to provide us with a comprehensive visual experience across different lighting conditions.

During a static task, vision serves several important functions. First, vision provides crucial information about the alignment and position of our body in relation to the environment (Winter et al., 1990). This visual input allows us to make small adjustments in our posture to maintain stability and prevent swaying or falling. In fact, visual cues from stationary objects in the environment serve as reference points that help us gauge our position and orientation (Peterka, 2018). These cues provide a stable frame of reference that we can use to adjust our posture and maintain balance. If we detect that our body is leaning or tilting slightly due to external factors, such as uneven surfaces, visual information allows us to identify these deviations and make appropriate corrections to maintain an upright posture. They can influence the activation of different muscles involved in maintaining posture (Perrin et al., 2009). Moreover, it is feedback of self movement when near enough from a wall or a target. It allows the modification of the visual field informing the CNS of self motion (L. R. Harris et al., 2000; Lappe et al., 1999). It also informs about the surroundings. By observing nearby objects and obstacles, we can identify spatial boundaries and obstacles that might affect our posture and stability and anticipate them (Mohapatra & Aruin, 2013). Maintaining attention on a specific visual point or object can help engage our cognitive focus during a static task (Gribble & Hertel, 2004). This can be particularly important for tasks that require sustained attention, such as monitoring equipment or reading instructions. Finally, visual feedback can enhance the sense of confidence and comfort by having a clear knowledge of our environment (Peters, 2022; van Bommel, 2015).

In summary, vision plays a critical role during a static task by helping maintain postural stability, make necessary adjustments, and navigate the environment effectively. Visual information serves as a valuable feedback mechanism, allowing us to align our body correctly, prevent falls, and ensure comfort and safety while performing stationary tasks.

Vision plays a fundamental role in goal detected locomotion. During a locomotor task such as walking, the visual system provides essential information to help detect and avoid obstacles such as other people, uneven surfaces, objects. Visually guided locomotion is essential to safe navigation and has received considerable attention in the literature (Mohler et al., 2007; Patla, 1998). It allows to perceive depth and distances to objects and surfaces (Mohagheghi et al., 2004). This information is essential for judging how far away objects are and making accurate decisions

about movement, such as stepping onto or over an obstacle. As in a static situation, the integration of visual cues inform the CNS of muscle adjustments needed to maintain balance and coordination (Mohapatra & Aruin, 2013). Moreover, visual cues allow us to estimate self speed and object speed (Durgin et al., 2005; Lappe et al., 1999). Vision helps us remain aware of our surroundings. This is particularly important in crowded or dynamic environments where we need to monitor the movements of others.

2.2. Evaluation

Evaluating the visual system involves assessing various aspects of vision, from basic visual acuity to more complex functions like depth perception and color vision:

- The **visual acuity** measures the sharpness and clarity of vision. The most common test for visual acuity is the Snellen chart, where individuals read letters or symbols from a distance to determine how well they can see (Holladay, 2004; Lovie-Kitchin, 1988).
- The **visual field** testing assesses the entire scope of vision, including peripheral vision. Tests like the confrontation test or automated perimetry evaluate any blind spots or visual field defects (Atchison, 1987).
- **Color vision** can be evaluated using tests like the Ishihara plates, which consist of patterns of colored dots, or the Farnsworth-Munsell 100 Hue Test, which assesses the ability to distinguish between subtle differences in colors (Swanson & Cohen, 2003).
- **Depth perception** is tested using methods like the stereopsis test, which assesses the ability to perceive depth and 3D structures. Other tests involve using special glasses to view images that require both eyes to see correctly (El Jamiy & Marsh, 2019).
- **Contrast sensitivity** evaluates the ability to distinguish objects from their background in various lighting conditions. Contrast sensitivity tests can identify issues not easily detected by standard visual acuity tests (Haymes et al., 2006).
- **Ocular motility** and alignment are evaluating how the eyes move and align in order to detect issues like strabismus (crossed or misaligned eyes) or nystagmus (involuntary eye movements) (Ansons & Davis, 2008; Thorn et al., 1994).
- **Pupil responses** to light can indicate the health of the optic nerve and neurological function. This evaluation can help diagnose conditions like optic nerve damage or brain injuries (Bremner, 2004).
- During visual **processing tests**, more complex assessments are realized to evaluate higher-level visual processing, such as visual memory, visual perception, and visual-motor coordination (Steese-Seda et al., 1995).
- **Refraction** determines the best prescription for corrective lenses, assessing any refractive errors like nearsightedness, farsightedness, or astigmatism.
- Comprehensive **eye exams** include a thorough evaluation of the eye's health, including the examination of the retina, optic nerve, and other structures. This helps detect conditions like glaucoma, macular degeneration, or diabetic retinopathy (Levin et al., 2011).
- Depending on specific concerns, additional tests might be needed, such as electroretinography (ERG) for assessing retinal function or optical coherence tomography (OCT) for detailed imaging of retinal layers.

It is important to note that visual evaluation can range from basic screenings to comprehensive assessments performed by eye care professionals such as optometrists or ophthalmologists.

B.3. Somatosensory system

The somatosensory system is complex and responsible for perceiving and processing various tactile sensations and proprioceptive information from the body. It encompasses the ability to sense and interpret touch, pressure, temperature, pain, and the position and movement of different body parts. This system plays a crucial role in the interaction with the environment, self-awareness, and motor control (Allum et al., 1998).

Its components are skin receptors, proprioceptors, nervous pathways, thalamus and primary somatosensory cortex. Sensory information collected by these receptors is transmitted through the nervous system via specialized pathways. There are two main pathways:

- The Dorsal Column-Medial Lemniscus Pathway transmits touch, pressure, and proprioceptive information to the brain for precise localization and discrimination.
- The Anterolateral Pathway transmits pain and temperature sensations to the brain. The sensory information is relayed to the thalamus, a crucial sensory relay station in the brain, and then are processed and integrated into the primary somatosensory cortex, located in the parietal lobe of the brain.

The somatosensory system allows us to perceive tactile perception (pressure, vibration, and texture, on the skin's surface), temperature perception (changes in temperature), pain perception and proprioception.

3.1. Proprioceptive system

This system provides information to the CNS about the position, movement, and orientation of body parts. Proprioception allows us to have an innate sense of where our body parts are located in space without needing to visually confirm their position. For example, you can touch your nose with your eyes closed because of proprioceptive feedback. Kinesthesia is closely related to proprioception and refers to the sense of movement and the ability to perceive the speed, direction, and force of body movements. This is important for coordinating smooth and controlled movements. Movements are executed by the muscular system.

There are three main types of muscles in the human body: skeletal muscles, smooth muscles, and cardiac muscles. Each type of muscle serves distinct functions and is found in different parts of the body. Skeletal muscles, also known as voluntary muscles, are the muscles that are attached to bones by tendons and enable us to perform voluntary movements. These muscles are responsible for locomotion, posture, and various voluntary actions like lifting, running, and jumping. They are under conscious control and are part of proprioceptive system (MacIntosh et al., 2006).

a. Anatomy

The proprioceptive system involves a complex network of sensory receptors, neural pathways, and brain regions. The localization of the receptors are muscles, joints and tendons.

There are several types of proprioceptive receptors located in different tissues of the body:

- Muscles spindles (Matthews, 1964):

They are specialized sensory receptors found within skeletal muscles. They are key components of the proprioceptive system, providing vital information about changes in muscle length and the rate of length change.

Each muscle spindle is a fusiform (spindle-shaped) structure located parallel to muscle fibers within the muscle belly. It consists of several specialized muscle fibers called intrafusal fibers, which are innervated by sensory nerve endings. These fibers are encapsulated by connective tissue and run parallel to the regular muscle fibers (extrafusal fibers) in the muscle. Intrafusal fibers are attached to the surrounding muscle tissue at both ends, and their central regions are more sensitive to stretch. The central region of intrafusal fibers contains sensory nerve endings known as primary sensory endings or annulospiral endings. These nerve endings are sensitive to the stretch of the intrafusal fibers (Figure 13).

They are sensitive to changes in muscle length. When a muscle containing muscle spindles is stretched or contracted, the intrafusal fibers within the spindle are also stretched or contracted. This leads to the activation of sensory nerve endings. They send signals to the spinal cord. From there, these signals are transmitted to the CNS, where they are interpreted to provide information about the changes. Muscle spindles are also sensitive to the rate of change in muscle length. The faster a muscle is stretched or contracted, the more the intrafusal fibers within the spindle are deformed, and the stronger the sensory signal generated (Tuthill & Azim, 2018).

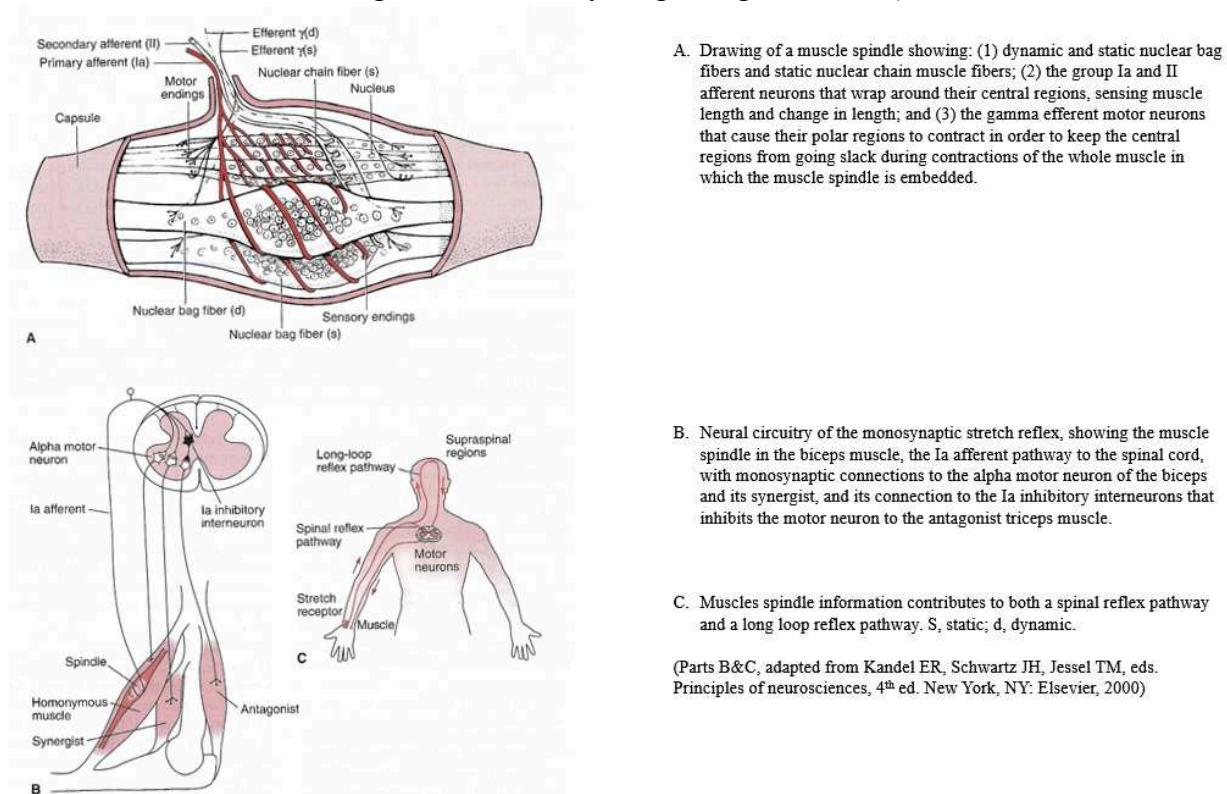


Figure 13: Anatomy of the muscles spindle (A, B and C:Shumway-Cook & Woollacott, 2007)

Muscle spindles are also involved in the stretch reflex, commonly known as the “knee-jerk reflex”. When a muscle is stretched rapidly, the muscle spindle detects the stretch and triggers a reflexive contraction of the muscle, helping to stabilize the joint (Dietz, 2002). This sensitivity to fast changes contributes to the precision of the feedback provided by muscle spindles.

The activation threshold for muscle spindles depends on various factors such as the speed of the muscle length change, the intensity of the stretch or contraction, as well as individual factors, can influence the activation threshold (Hurley, 1997).

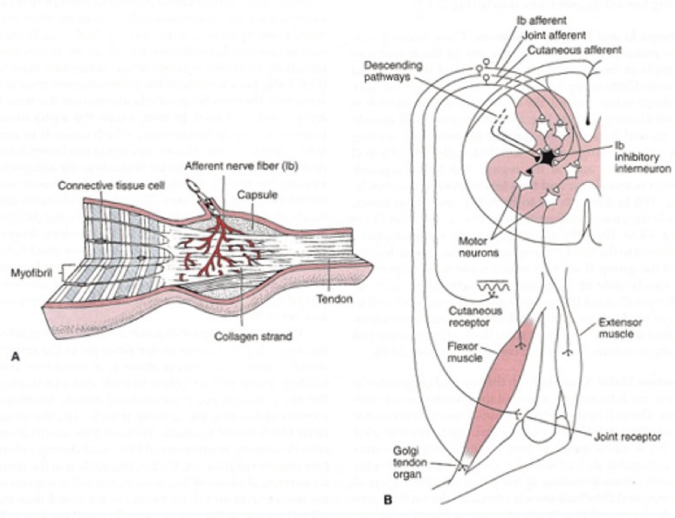
Muscle spindles are designed to detect minimal changes in muscle length (fraction of millimeters) and provide accurate information to the nervous system about body position and movement (Valenčič & Knez, 1997).

- Golgi Tendon Organs (GTOs):

They are specialized sensory receptors located at the junction between muscles and tendons. These receptors play a crucial role in providing feedback to the nervous system about muscle tension and force (Tuthill & Azim, 2018).

GTOs consist of bundles of collagen fibers that are intertwined with the muscle fibers and their associated tendons. These collagen bundles are arranged in a way that makes them sensitive to changes in tension. Within the Golgi tendon organ, sensory nerve endings are intertwined among the collagen bundles. These nerve endings are known as "Golgi tendon receptor nerve endings". The entire structure is enclosed within a connective tissue capsule. This capsule helps protect the Golgi tendon organ and maintain its integrity (Schoultz & Swett, 1972).

GTOs play a critical role in detecting changes in muscle tension and force during muscle contraction. They code for tension sensing. When a muscle contracts and exerts force, the tension generated is transmitted to the attached tendon. This tension causes the collagen fibers in the Golgi tendon organ to stretch. This leads to the activation of the sensory nerve endings within the Golgi tendon organ which send signals to the spinal cord and CNS to inform them about the level of muscle tension being generated (Kandel et al., 2000) (Figure 14).



A. Golgi tendon organ and its Ib afferent innervation. It is located at the muscle-tendon junction and is connected to 15 to 20 muscles fibers.

B. Neural circuitry of the Golgi tendon organ (GTO) reflex pathway, showing the GTO in the biceps muscle. Ib afferent information from the GTO synapses onto Ib inhibitory interneurons, which inhibit motor neurons to the agonist muscle and also disinhibit motor neurons in the antagonist triceps muscle.

(Part B adapted from Kandel ER, Schwartz JH, Jessel TM and al., eds. Principles of neurosciences, 5th ed. New York, NY: McGraw Hill, 2013, with permission.)

Figure 14: Golgi tendon organ (Shumway-Cook, 2007)

One of the key functions of GTOs is to initiate the “Golgi tendon reflex”, also known as the inverse myotatic reflex. This reflex serves as a protective mechanism against excessive muscle force. When Golgi tendon organs detect high tension in the muscle, they send inhibitory signals to the spinal cord, which results in relaxation of the muscle. This prevents muscle and tendon damage due to excessive force. They also contribute to motor control by regulating muscle force during voluntary movements (Jami, 1992). They help prevent overexertion and maintain safe levels of force production. This is particularly important to prevent injuries.

GTOs sensitivity can be modulated based on the level of muscle activity. During intense or prolonged muscle contractions, GTOs become more sensitive, providing the nervous system with feedback about the level of force being exerted. The relative insensitivity of GTOs to low levels of tension is essential for preventing unnecessary inhibition of muscle contractions during normal activities (Fallon & Macefield, 2007).

- Joint receptors:

Joint receptors are sensory structures located within and around the joints of the body. These receptors play a critical role in providing information to the nervous system about the position, movement, and pressure changes within the joints. They are essential for maintaining proper joint stability, coordinating movements, and ensuring accurate body awareness.

There are several types of joint receptors, each with specific functions and distributions within the joint (Macefield, 2005) (Figure 15).

The “Pacian corpuscles” are pressure-sensitive receptors found in the joint capsule and ligaments. They respond to rapid changes in joint position and transmit information about joint movement.

The “Ruffini endings” are mechanoreceptors located in the joint capsule and ligaments. They are sensitive to changes in joint angle and contribute to the sense of joint position.

The “free nerve endings” are distributed throughout joint tissues, including the synovial membrane, ligaments, and surrounding soft tissues. They respond to various mechanical stimuli, such as pressure, tension, and movement.

The “Golgi-Like Receptors” look like GTOs and are found in joint capsules. They contribute to proprioception by providing information about joint tension and movement.

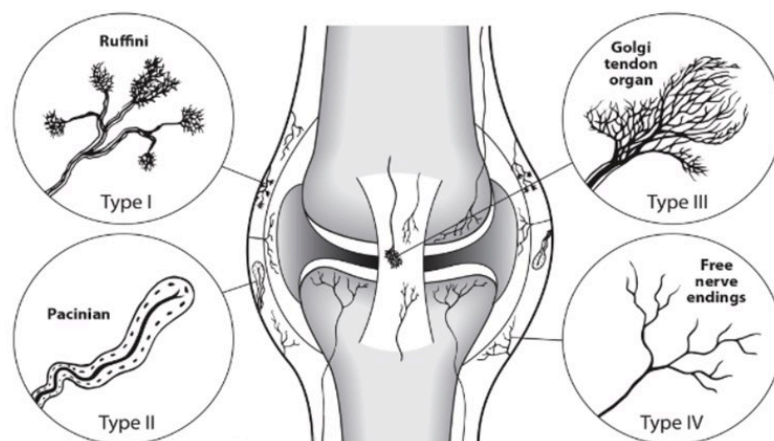


Figure 15: Joints receptors (example of the knee joint) (courtesy of www.caringmedical.com)

b. Functions

They have different functions. They provide information about the angle and position of a joint. As a joint moves, the distribution of pressure and tension on joint receptors changes. These receptors detect these changes and provide feedback to the CNS, enabling it to accurately perceive movement. That information contributes to joint stability by providing real-time information about the joints position and orientation. They play a role in preventing joint damage by signaling the brain when a joint is at risk of reaching its physiological limits or being subjected to excessive force (Ferrell et al., 1987).

Proprioceptors work together in a coordinated manner to provide the CNS with comprehensive information about body position, movement, and orientation. They all together contribute to unique sensory information. Through their interactions, they help maintain balance, coordinate movements, and ensure proper spatial awareness (Tuthill & Azim, 2018).

When a muscle contracts or stretches, both muscle spindles and Golgi tendon organs are activated. Muscle spindles inform the brain about the muscle's length and contraction speed, while Golgi tendon organs provide information about muscle force. Together, they help the brain regulate muscle tone, adjust force production, and maintain muscle coordination (Kistemaker et al., 2013). Joint receptors work with muscle spindles to provide information about joint position and movement. As the muscles around a joint contract or relax, joint receptors contribute to the sense of joint angle and movement, allowing the brain to accurately perceive limb position (Hurley, 1997). Proprioceptive feedback also fine-tunes movement accuracy. Vestibular receptors contribute to overall balance and spatial orientation. They interact with visual information and proprioceptive feedback to help us maintain our equilibrium while moving and changing positions. Proprioceptive information is integrated with other sensory, such as the vestibular system and visual system. This integration helps us make minute adjustments to body alignment to prevent falls or imbalance. Proprioceptors also contribute to the awareness of body position without the need for visual feedback. This is especially important when eyes are closed.

This multisensory integration creates a unified perception of body position and movement in relation to the environment. The brain processes proprioceptive input and generates appropriate motor commands to control muscle contractions and adjust movement patterns. Reflexes are triggered to protect muscles and maintain posture. Proprioceptive input is integrated with other sensory cues to create a cohesive perception of body position and movement even when we are not actively engaged in dynamic activities (Sober & Sabes, 2003).

During a static task, muscle spindles provide feedback about the degree of muscle contraction and tension, helping to regulate muscle tone. This ensures that the muscles are neither overly contracted nor overly relaxed, maintaining a balanced and stable posture (Hassan et al., 2001).

Meanwhile, GTOs monitor muscle tension. and provide information about the level of force being exerted on the muscles. This information helps prevent excessive muscle contraction, which could lead to fatigue or discomfort. Joint receptors contribute to maintaining a stable joint position by providing information about joint angles and pressure changes within the joints. minor adjustments are continually made to maintain stability. Reflexes triggered by proprioceptors help regulate muscle tone and maintain joint stability (Massion, 1994).

During a locomotor task, proprioceptors contribute to kinesthetic awareness, particularly during locomotion (environment obstacles detection). They provide feedback about the extent and speed of muscle contractions and stretches and ensure that the right muscles contract at the right time and with the appropriate force. They manage dynamic adjustments with reflex control. The minute sensitivity of the proprioceptive system is especially important for fine motor control. When engaging in delicate tasks or intricate movements, the brain relies on their feedback to adjust muscle contractions accurately. They also interact with other inputs (vestibular, visual) to maintain the accurate navigation or motion (Dietz, 2002).

3.2. Skin receptors

Skin receptors are specialized sensory structures located within the skin that permit it to perceive various sensations related to touch, pressure, temperature, and pain. These receptors are essential for interactions with the external environment and play a crucial role in providing information about the objects touched, the temperature of the surroundings, and eventual threats to our well-being (Roosterman et al., 2006) (Figure 16).

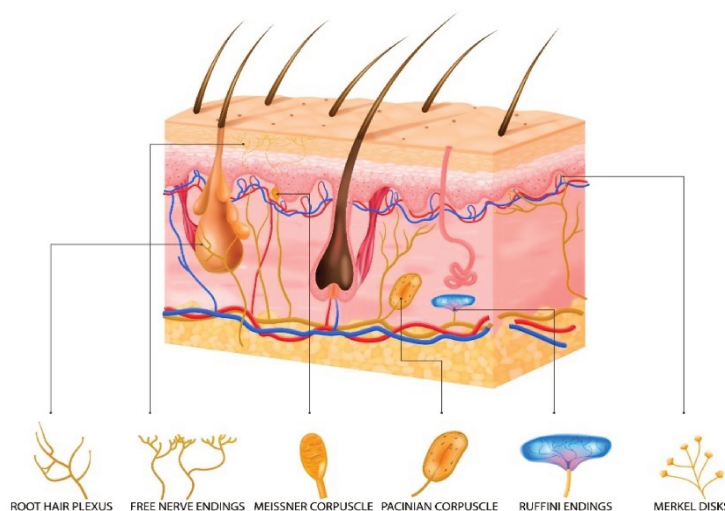


Figure 16: Skin receptors (www.biorender.com)

a. Anatomy and function

There are 4 categories of skin receptors based on their function (Vallbo & Johansson, 1984).

- Mechanoreceptors (K. Johnson, 2001)

Merkel cells are found in the *stratum basale* of the epidermis (the outermost layer of the skin). They are typically located close to nerve endings, forming a specialized sensory unit known as a Merkel cell-neurite complex. The primary function of Merkel cells is to contribute to tactile sensation, particularly in the context of touch discrimination. They work in conjunction with nerve endings to detect mechanical stimuli, such as pressure and indentation, which helps us perceive detailed information about the objects we touch. Merkel cells are especially sensitive to sustained

pressure and are responsible for our ability to distinguish fine textures and shapes on the skin's surface, even without relying on visual cues.

Merkel cell-neurite complexes facilitate communication between Merkel cells and sensory nerve fibers, allowing for the transmission of tactile information to the CNS. The nerve fibers associated with Merkel cells are specialized mechanoreceptors that respond to mechanical deformation and pressure. When pressure is applied to the skin, the complex is activated. This activation generates electrical signals that travel along the nerve fibers to the brain where they get interpreted as tactile sensations.

Merkel cells exhibit a slow rate of adaptation to pressure. This means that they continue to generate signals as long as pressure is maintained on the skin. This property makes Merkel cells well-suited for detecting sustained pressure and maintaining continuous tactile feedback during interactions with objects.

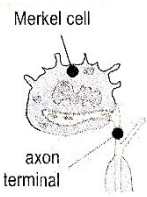
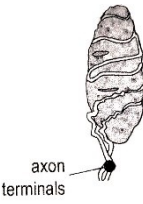
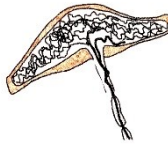

Meissner's corpuscles are elongated structures located in the dermal papillae, which are small projections of the dermis into the epidermis. Each corpuscle consists of a stack of flattened cells, surrounded by connective tissue and encapsulated by Schwann cells. Their function is to detect light touch and changes in textures on the skin's surface. They are highly sensitive to mechanical deformation and vibrations, making them particularly suited for detecting subtle changes in surfaces. When an object comes in contact with the skin, it causes the skin to deform and compress the Meissner's corpuscles within the dermal papillae. This deformation generates electrical signals that travel along sensory nerve fibers to the CNS where they are interpreted as sensations of touch. They are especially sensitive to light touch and low-frequency vibrations. They excel at detecting rapid changes in pressure and texture. This sensitivity allows us to discriminate between different textures and materials, contributing to our ability to recognize objects based on touch alone. They exhibit rapid adaptation to continuous pressure. Their firing rate decreases quickly when pressure is maintained, allowing them to respond to changes in pressure rather than constant stimulation. This property is important for detecting dynamic changes in surfaces and textures.

Pacinian corpuscles are oval-shaped structures that consist of concentric layers of connective tissue and nerve fibers. They are encapsulated by Schwann cells and connective tissue layers. They are located in the deeper layers of the skin's dermis, as well as in other tissues such as tendons, ligaments, and internal organs. Their function is to detect mechanical stimuli, particularly rapid vibrations and changes in pressure. They are highly sensitive to mechanical deformation and can respond to stimuli over a wide range of frequencies, including those in the high-frequency spectrum. When a mechanical stimulus, such as a vibration or a tap, is applied to the skin, it deforms the layers of the Pacinian corpuscle. This deformation triggers the activation of sensory nerve fibers within the corpuscle. The nerve fibers then transmit electrical signals to the brain, which interprets these signals as tactile sensations, allowing us to perceive vibrations and rapid changes in pressure. They are particularly sensitive to vibrations in the high-frequency range. They respond strongly to the initial change in pressure or vibration but quickly reduce their firing rate if the stimulus is maintained.

Ruffini endings are spindle-shaped structures with elongated capsules made of collagen fibers. They are encapsulated by connective tissue and are found in the deep layers of the skin's dermis, as well as in joint capsules, ligaments, and tendons. Their function is to detect mechanical changes in the skin and surrounding tissues, especially those related to skin stretch and deformation. They are responsible for providing information about skin tension and pressure variations. When the skin or surrounding tissues are stretched or deformed, the collagen fibers within the Ruffini ending's capsule are also stretched. This mechanical deformation leads to the activation of sensory nerve fibers within the corpuscle. These nerve fibers transmit electrical signals to the brain, which interprets these signals. They play a role in detecting continuous pressure and show slow adaptation to continuous stimuli. They continue to generate continuous feedback as long as the mechanical deformation or stretch is maintained.

Those receptors (Table 1) have temporal and spatial adaptation properties: fast or slow. Their receptive field sizes correlate with their tactile spatial acuity.

Table 1: Cutaneous mechanoreceptors organs (Tresilian, 2012)

Receptor	Merkel Disk receptors	Meissner corpuscle	Ruffini end organ	Pacinian Corpuscle
Diagram				
Fiber group	A β	A β	A β	A β
Adaptation characteristic	Slow adapting	Fast adaptation	Slow adapting	Fast adaptation
Skin type	Glabrous and hairy	Glabrous and hairy	Glabrous and hairy	Glabrous and hairy

- Thermoreceptors (Hensel, 1974)

Warm receptors are sensitive to increases in skin temperature and contribute to the perception of warmth.

Cold receptors are sensitive to decreases in skin temperature and contribute to our perception of cold.

- Nociceptors (R. Schmidt et al., 1995)

Nociceptors are pain receptors that detect harmful or potentially damaging stimuli, such as extreme temperatures, pressure, or tissue damage. They are essential for alerting us to potential threats and prompting protective responses.

b. Foot specificities

- Distribution (Kennedy & Inglis, 2002)

These receptors are distributed across the skin of the entire body. However, different areas of the body, including the feet, may have varying densities and concentrations of these receptors. The feet, in particular, exhibit certain specificities in terms of receptor distribution and sensitivity due to their role in supporting our body weight, facilitating locomotion, and interacting with surfaces. Merkel cells are present in areas that require precise tactile discrimination, such as the fingertips and the tips of the toes. They are also found in hairless areas of the feet, where fine touch and tactile detail are essential. Meissner's corpuscles are densely concentrated in areas of the skin that are highly sensitive to touch and tactile discrimination. In the feet, they are more abundant in regions such as the fingertips, the tips of the toes, and the soles of the feet, especially in the areas that experience more direct contact with surfaces. Pacinian corpuscles are present in the skin and connective tissues throughout the body, including the feet. They are relatively more abundant in areas with thicker skin and in regions that experience frequent pressure changes, such as the soles of the feet (Figure 17) (Strzalkowski et al., 2018). Ruffini endings are found in the deep layers of the skin, including the feet. They are present in areas that experience stretching and deformation, such as the soles of the feet and the skin over joints, ligaments, and tendons.

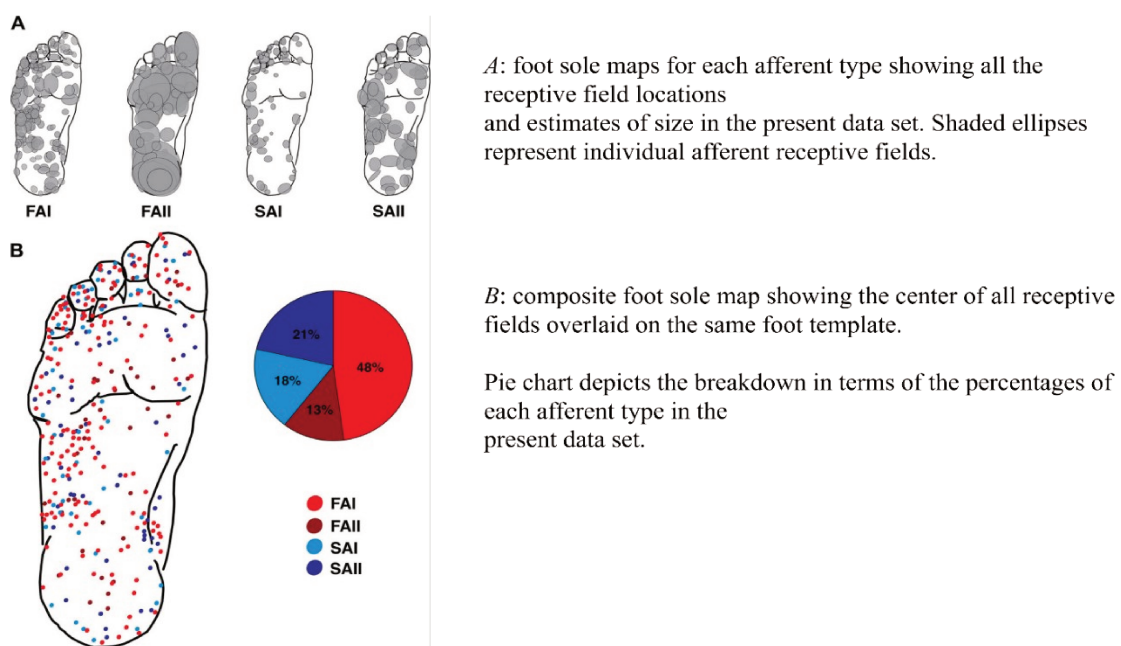


Figure 17: Receptive fields of the different cutaneous mechanoreceptor classes. (Strzalkowski et al. 2018)

- Functions (Inglis et al., 2002)

They play essential roles in facilitating various functions that are crucial for the foot interaction with the environment and its role in supporting the body during locomotion (Table 2).

Meissner's corpuscles allow us to perceive the tactile properties of different surfaces as we walk or stand. They help us detect and respond to the textures and contours of the ground beneath our feet, enhancing our ability to navigate and adjust our movements based on tactile feedback.

Pacinian corpuscles contribute to our ability to perceive vibrations caused by locomotion. They help us detect changes in ground surfaces and respond to the impact forces associated with different types of terrain.

Ruffini endings contribute to our ability to sense the pressure distribution under foot during standing, walking, and other weight-bearing activities. They also help us detect stretching of the skin as the foot moves and adapts to different positions. Merkel cells enable us to discern the textures of surfaces that come in contact with the skin. They allow us to detect and differentiate between various textures, enhancing our ability to sense the qualities of surfaces as we walk and explore with our feet.

Table 2: Somatosensory afferent fiber groupings (Tresilian, 2012)

Mechanoreceptors	Effective sensation
Merkel Disks	Sustained skin contact and pressure, slowly changing skin deformations (frequencies less than 5Hz)
Meissner Corpuscles	Lateral movement, vibration and fairly rapid changes in skin deformation (5 to 50 Hz)
Ruffini end organs	Sustained and slow changes in skin stretch or tension
Pacinian corpuscles	High frequency vibration (40 to 400 Hz), contact events and rapid skin deformations

c. Evaluation

The evaluation of skin receptors involves various sensory tests designed to assess their responsiveness and functionality. Here are some common methods used to evaluate these receptors (Bell-Krotoski et al., 1993; K. Johnson, 2001; Novak, 2001):

- **Two-Point Discrimination Test** (Aszmann & Dellon, 1998; A. L. Dellon, 1978; Nolan, 1983):

This test assesses the ability to perceive two distinct points of contact on the skin. It is commonly used to evaluate the density and sensitivity of Meissner's corpuscles, which are responsible for fine touch discrimination. The smaller the distance between the two points that can be distinguished, the higher the density of Meissner's corpuscles.

- **Vibration Sensation Test** (Bensmaïa et al., 2005; Gerr & Letz, 1988; Posnick et al., 1990; Vinik et al., 1995):

This test involves applying a vibrating tuning fork or a specialized device to the skin and assessing the individual's ability to detect and perceive the vibration. It assesses the sensitivity of Pacinian corpuscles, which are sensitive to vibrations and rapid changes in pressure.

- **Pressure and Texture Discrimination Tests** (E. S. Dellon et al., 1997; Dyck et al., 1978):

These tests involve applying various levels of pressure to the skin using specialized instruments. The individual is asked to identify the pressure level or describe the texture perceived during the test. These tests evaluate the functionality of Ruffini endings and Merkel cells, which are sensitive to skin stretch, sustained pressure, and fine textures.

- **Point Localization Test** (Hoagland, 1932):

In this test, a small point or dot is lightly applied to the skin, and the individual is asked to identify the exact location where the stimulus was applied. This test assesses the accuracy of touch perception and the ability to locate specific points on the skin's surface.

- **Tactile Grating Test** (Boven & Johnson, 1994; K. O. Johnson et al., 2000):

A tactile grating instrument with grooves of varying distances is applied to the skin. The individual is asked to identify the orientation of the grooves. This test assesses the ability to perceive changes in texture and is sensitive to the functionality of Meissner's corpuscles and Merkel cells.

- **Quantitative Sensory Testing (QST)** (Siao & Cros, 2003; Zaslansky & Yarnitsky, 1998):

QST involves systematically applying controlled stimuli, such as heat, cold, pressure, and vibration, to the skin and recording the individual's perception of these stimuli. QST allows for the quantitative assessment of sensory thresholds and provides information about the sensitivity of different types of receptors (Fujimoto et al., 2012; Riviere et al., 1991; D. Schmidt et al., 2017).

- **Neurological Examinations:**

Neurologists may perform clinical examinations that involve assessing sensory perception in different areas of the body, including the feet. These examinations help detect any abnormalities in the function of skin receptors and other sensory pathways. It include the previous tests but also temperature sensation test (Golja et al., 2003), pinprick test (Chan et al., 1992), proprioception test(position sense of a toe for example) (Clark et al., 1979), graphesthesia test (Bender et al., 1982), stereognosis test (Byl et al., 2002).

It is important to note that evaluating skin receptors is often part of a comprehensive sensory assessment that includes other components of the somatosensory system, such as proprioception and pain perception. Additionally, specialized equipment, such as sensory testing devices and instruments, may be used to standardize the evaluation process and gather accurate measurements of sensory thresholds and perceptions.

B.4. Sensory systems interactions

All relevant sensory information is processed by the central nervous system to maintain the desired balance and posture of the individual, whether in static or dynamic situations. We will focus on static and dynamic balance, as well as the role and evaluation of afferent systems in these situations.

The vestibular apparatus interacts with visual and proprioceptive systems. The semicircular canals detect rotational movements of the head, and this information is transmitted to the CNS. Simultaneously, the visual system perceives the movement of the surrounding environment. The CNS integrates signals from both the semicircular canals and the visual system to stabilize the visual field. This stabilization enables to maintain a steady view even when the head is in motion. This is linked also to the vestibulo-ocular reflex (VOR). It is a significant interaction between the vestibular system and vision. When the head moves, the VOR ensures that the eyes move in the opposite direction to the head movement. For instance, when you turn your head to the left, your eyes will move to the right to keep your gaze fixed on a point. This stabilizes vision during head movements, enhancing visual perception during activities like walking (Cullen, 2012).

The ocular tilt reflex, also known as the subjective visual vertical (SVV) (Böhmer & Rickman, 1995; Dyde et al., 2006), is a sensory-motor response of the eyes and head that helps maintain visual and postural orientation with respect to gravity. It is a fundamental mechanism that allows to perceive verticality and adjust the head and eye movements to align with self-perception of "up" and "down."

The interaction between visual and vestibular systems is also observed when the environment is dark or when there is a lack of visual cues. In those situations, the visual system might be less accurate in perceiving movements. In such cases, the vestibular system becomes more important for maintaining balance and movement coordination. Similarly, if the vestibular system is impaired, the visual system plays a more significant role in compensating for imbalances. It is a reweighting process (Bent et al., 2002; Black et al., 1988). Information about head movements and the adjustments needed to maintain balance is used by the CNS to assess the distance of objects and the spatial arrangement of the environment. This contributes to the perception of depth and distance (Dokka et al., 2011).

Proprioception provides information about the position of muscles, joints, and body segments, while the vestibular system detects changes in head position and angular velocity. Together, these systems help maintain balance and posture. The CNS simultaneously receives proprioceptive information from muscles, joints, sensors but also from the vestibular system.

Both allow to make precise adjustments in muscle activity to maintain balance. That information is entwined.

More of a key role in balance, they participate in the perception of the body position and movement in 3-dimensional space. They contribute to prevent falls by correcting movement when needed and ensure coordination. Proprioceptive signals from neck muscles and visual input also contribute to the perception of verticality. These cues help CNS integrate sensory information to determine the true vertical orientation and adjust the alignment of the head and eyes accordingly.

They support sensorimotor learning. Over time, CNS refines its ability to interpret and integrate sensory inputs from both systems, resulting in improved balance, movement precision, and adaptability (Cullen, 2012).

Visual information interacts with other sensory inputs in a process known as multisensory integration. This integration enhances understanding of the world and helps us make more accurate and adaptive responses to various situations. As said before, the vestibular and the visual systems inputs are integrated together to accurately perceive self motion in relation to the environment in order to maintain balance and spatial orientation. For the same purpose, vision and proprioception collaborate to create a sense of body position and movement (van Beers et al., 1999). This spatial awareness is helping proprioceptive feedback to maintain balance and control posture. For example, during a single leg balance test, CNS uses visual cues to adjust body position based on the visual horizon, while proprioceptive input from the leg's muscles and joints provides information about the body's position and movement.

This is crucial for motor coordination whether in balance tasks or in daily action, like grabbing an object. Visual information about the object's location is combined with proprioceptive feedback from arm muscles to realize an accurate movement. Visuo-proprioceptive integration helps update and refine the body schema (mental representation of the body's shape, size, and position) based on the current sensory inputs, allowing a safe interaction with the environment.

Likewise, this integration plays a role in both egocentric (self-centered) and allocentric (environment-centered) spatial processing. It allows the perception of objects and locations in relation to the body as well as in relation to other objects in the environment (Sober & Sabes, 2003; van Beers et al., 1999).

Overall, visuo-proprioceptive integration is a fundamental process that allows us to interact with the world effectively, move our bodies with precision, and maintain a stable sense of self and space. It's a dynamic interplay between visual and proprioceptive inputs that contributes to our overall perception and motor control (D. N. Lee & Lishman, 1975).

Multisensory integration also occurs between vision and the somatosensory system. Feet and hand soles are particularly included in this integration (Bronstein, 2016; Shaffer & Harrison, 2007; Stein & Stanford, 2008). While having an upright posture, feet soles are the body part touching the environment. Hands are prehension organs and used to carry or touch objects. Activities that require hand-eye coordination, such as catching a ball or threading a needle, rely on the integration of visual information about the target, proprioceptive feedback from the limbs involved in the movement, and cues from the somatosensory system.

Auditory and olfactory systems are also included in the integration with visual systems (Barnett-Cowan & Harris, 2009). For example, when you see a person speaking, you automatically integrate their lip movements with the sound of their voice to improve speech comprehension. Or a sound while crossing a street alerts about a possible danger and triggers a body reaction (Morein-Zamir et al., 2003). Visual stimuli can evoke emotional responses, which can in turn influence other sensory perceptions. For instance, seeing a frightening scene might increase your heart rate and alter your auditory perception by making you more attuned to potential threats (Gray, 2004). Overall, the interaction of visual information with other sensory inputs is a complex and dynamic process that enriches our perception, enhances our understanding of the environment, and allows us to respond effectively to various situations (Letts et al., 2022). This integration is person-dependent and linked to the intrinsic capabilities of individuals (Basharat et al., 2019).

All these systems are integrated to enable the individual to perform actions safely. They play a role in both static and dynamic balance.

C. Static balance

C.1. Definitions, mechanisms and assessment

1.1. Definitions and mechanisms

Static balance is the ability of an individual to maintain an upright and stable posture while being stationary. Maintaining static balance is a complex process that involves the integration of sensory information, motor control and biomechanical adjustments (Alexander & Kinney LaPier, 1998; Shumway-Cook & Woollacott, 2007; Tresilian, 2012).

Achieving stability in static balance involves maintaining the body's center of mass over its base of support, minimizing swaying or tilting, and preventing falls. The concept of equilibrium is central to understanding how the body maintains stability. To achieve equilibrium, the body Center of Mass (CoM) has to be positioned over its Base of Support (BoS) (Tresilian, 2012; Winter et al., 1990) (Figure 18). Equilibrium refers to a state in which an object or system has balanced forces

acting on it, causing it to remain stationary or moving with constant velocity (not accelerating). Stability, on the other hand, is related to how an object or system responds to disturbances or small displacements from its equilibrium position.

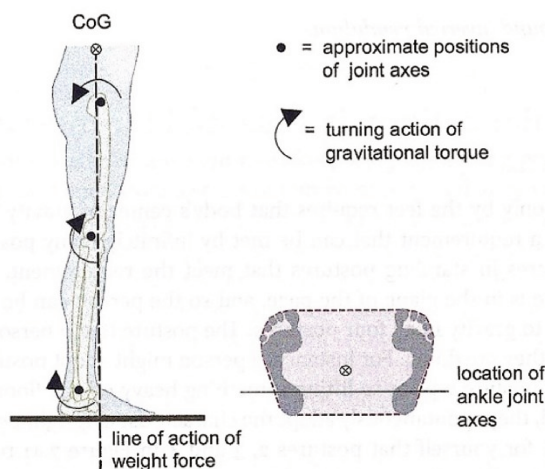


Figure 18: Gravitational torques about the ankles, knee and hip joints when standing upright (Tresilian, 2012)

CoM is the theoretical point where its mass is evenly distributed. It is the average location of the body's mass. To calculate the CoM, the body is divided into segments (head, arms, legs, trunk), and the CoM of each segment is estimated based on anatomical landmarks and known segment masses based on anthropometric tables (Winter, 2009). These segmental CoMs are then combined to estimate the whole-body CoM. It is used to simplify the body system in a point (Clauser et al., 1969).

The BoS refers to the area on which an object or a person makes contact with the supporting surface, such as the ground (Figure 18). It can vary in size and shape. In standing posture, it typically includes the area covered by both feet when they are in contact with the ground. The shape can change if the feet are placed together or apart, or if one foot is lifted. When the base of support is wider, the projection of the CoM has more space to move within it without causing the body to tip over (Latash et al., 2010).

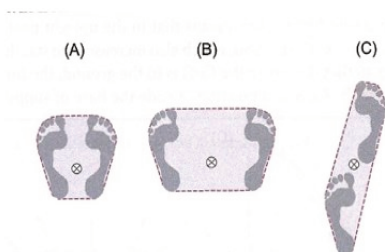


Figure 19: The base of support (shaded) with the feet in different positions (Tresilian, 2012)

Equilibrium is not a fixed state but rather a dynamic process involving continuous adjustments. To make those adjustments, the body constantly relies on a sensory feedback loop about its

orientation in space and makes reflexive and voluntary movements to counteract deviations from a stable posture (Figure 20).

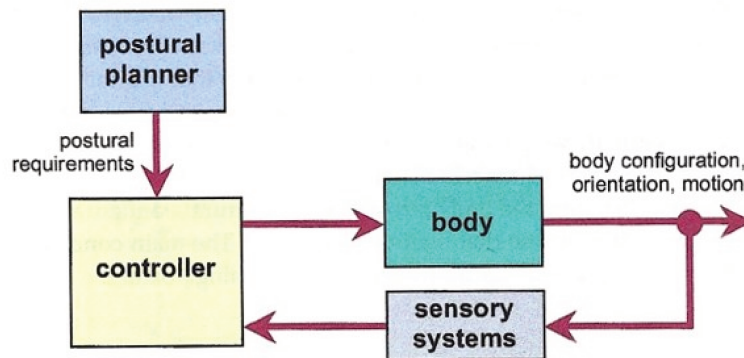


Figure 20: Sensory feedback loop in the postural control (Tresilian, 2012)

Several strategies have been proposed to explain how the body maintains stability during stationary positions (Figure 21). Ankle strategy focuses on the contributions of the ankle joint and the muscles surrounding it. It suggests that the body primarily uses adjustments at the ankle joint to maintain stability. Muscles in the lower legs are activated to control small perturbations and shifts in body weight. Hip strategy is similar to the ankle strategy. In situations where the ankle strategy may not be sufficient, the body engages larger muscles around the hips to stabilize the body. The “change in base of support” strategy centers around the concept that the body adjusts its base of support to maintain balance. By altering the positioning of the feet or other body parts, the body can stabilize itself (Runge et al., 1999). The sensory integration model emphasizes the role of sensory information from the afferences systems.

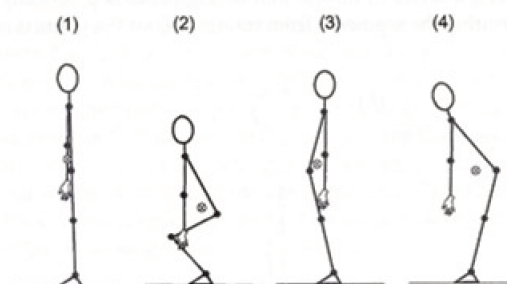


Figure 21: Four different upright postures in which the CoM is above the base of support (Tresilian, 2012)

To describe these strategies, the “inverted pendulum” model simplifies the representation of the human body. The concept of this pendulum is closely related to the theory of balance and equilibrium, especially in the context of human posture and locomotion (Loram & Lakie, 2002). The inverted pendulum model is often used to describe the mechanics of how humans maintain balance during walking and other forms of dynamic movement (Milton et al., 2009).

In this model, the human body is likened to an upside-down pendulum, where the body's center of mass is located above the point of contact with the ground. This model simplifies the body's

mechanics for analyzing balance and gait. CoM movement analysis describes the pendulum continuous movement (Gage et al., 2004) (Figure 22).

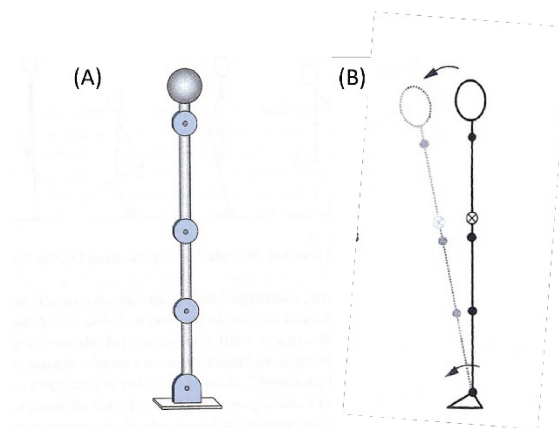


Figure 22: (A) a compounded inverted pendulum. (B) Sway in upright stance around ankle joints (adapted from Tresilian, 2012)

2.2. Assessment of static balance

Assessment of static balance often involves the use of a force platform. This device is used to measure the forces and torques applied to it by a person standing (or performing other static activities). It provides data about an individual's distribution of weight, center of pressure (CoP) movement. The CoP refers to the point on a force platform where the resultant force of the vertical ground reaction forces is applied. By monitoring the movement of the CoP, researchers and clinicians can analyze an individual's balance and postural control. The CoP trajectory provides insights into how weight distribution changes and how an individual adjusts to maintain stability (Figure 23). A stable CoP indicates that the individual's weight distribution is centered over the BoS. If the CoP moves outside it, it suggests a shift in weight and potential balance challenges. The movement of the CoP over time is known as postural sway. Postural sway involves oscillations in both amplitude (how much the body moves) and frequency (how quickly it moves). These oscillations are generally very small and happen at a rate of about 0.1 to 2 Hz. It tends to increase with age, as well as in individuals with balance impairments or certain medical conditions (Abrahamová & Hlavačka, 2008; Teasdale et al., 1991). Excessive or irregular postural sway can be indicative of balance deficits (Massion, 1994; Newell et al., 1993; Ruhe et al., 2010).

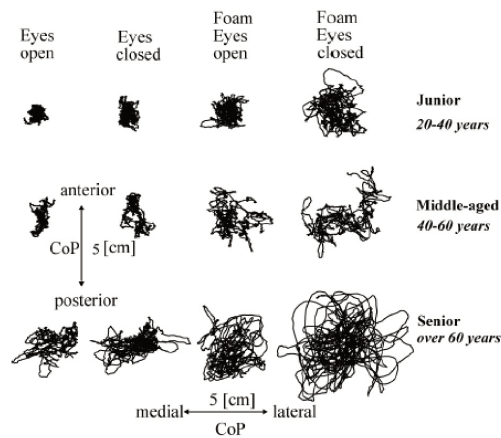


Figure 23: The statokinesigrams in four tested conditions for typical subjects from three age categories. The increase of COP displacement is evident with age in each condition (Abrahamova, 2008)

Various parameters are measured and quantified to characterize the extent, frequency, direction, and patterns of the CoP movement during static standing. Sway amplitude refers to the distance the CoP moves from its mean or reference position. It reflects how much the body sways back and forth or side to side (Blaszczyk et al., 2011). Larger sway amplitudes can indicate reduced stability. Sway area represents the area covered by the CoP trajectory on the force platform. A larger sway area indicates more overall movement. Sway velocity measures how quickly the CoP moves. It quantifies the speed of postural sway oscillations (Yamamoto et al., 2015). Higher sway velocities may suggest difficulty in controlling balance. As the recording time is standardized, the sway velocity is directly linked to the length of the CoP displacement. Sway frequency indicates how many oscillations occur within a specific time frame. It's measured in Hertz (Hz). Frequencies within the range of 0.1 to 2 Hz are common in postural sway analysis. Parameters such as mean sway amplitude, standard deviation, root mean square, and range provide statistical summaries of the sway data, helping to describe the variability and extent of postural sway (Kim et al., 2010; Palmieri et al., 2002) (Figure 24). Postural sway can occur in different directions (forward-backward, side-to-side). Quantifying sway in specific directions can provide insights into which directions might be more challenging for an individual. Some analyses involve breaking down postural sway data into frequency components using methods like Fourier analysis or wavelet transforms (Sezer & Ferdjallah, 2005). This can help identify dominant frequencies and patterns of sway. Complexity measures, such as sample entropy or approximate entropy, assess the irregularity or randomness of postural sway data (Ramdani et al., 2009). These measures offer insights into the body's control strategies.

Postural sway parameters can be compared between individuals or groups to identify differences related to age, health conditions, interventions, or other factors (Vuillerme et al., 2008). Researchers and clinicians often compare postural sway parameters between different conditions (e.g., eyes open vs. eyes closed, stable vs. unstable surface) to understand how factors influence balance control (Shumway-Cook & Horak, 1986).

To minimize individual variability, test-retest is done in the same condition. 3 to 5 repetitions seem to be necessary to obtain valuable data on all parameters for a 30 second trial and 2 for a 120 s one. Length and velocity of CoP motion were shown to be more reproducible than its area in-between comparison (Ruhe et al., 2010; Salavati et al., 2009).

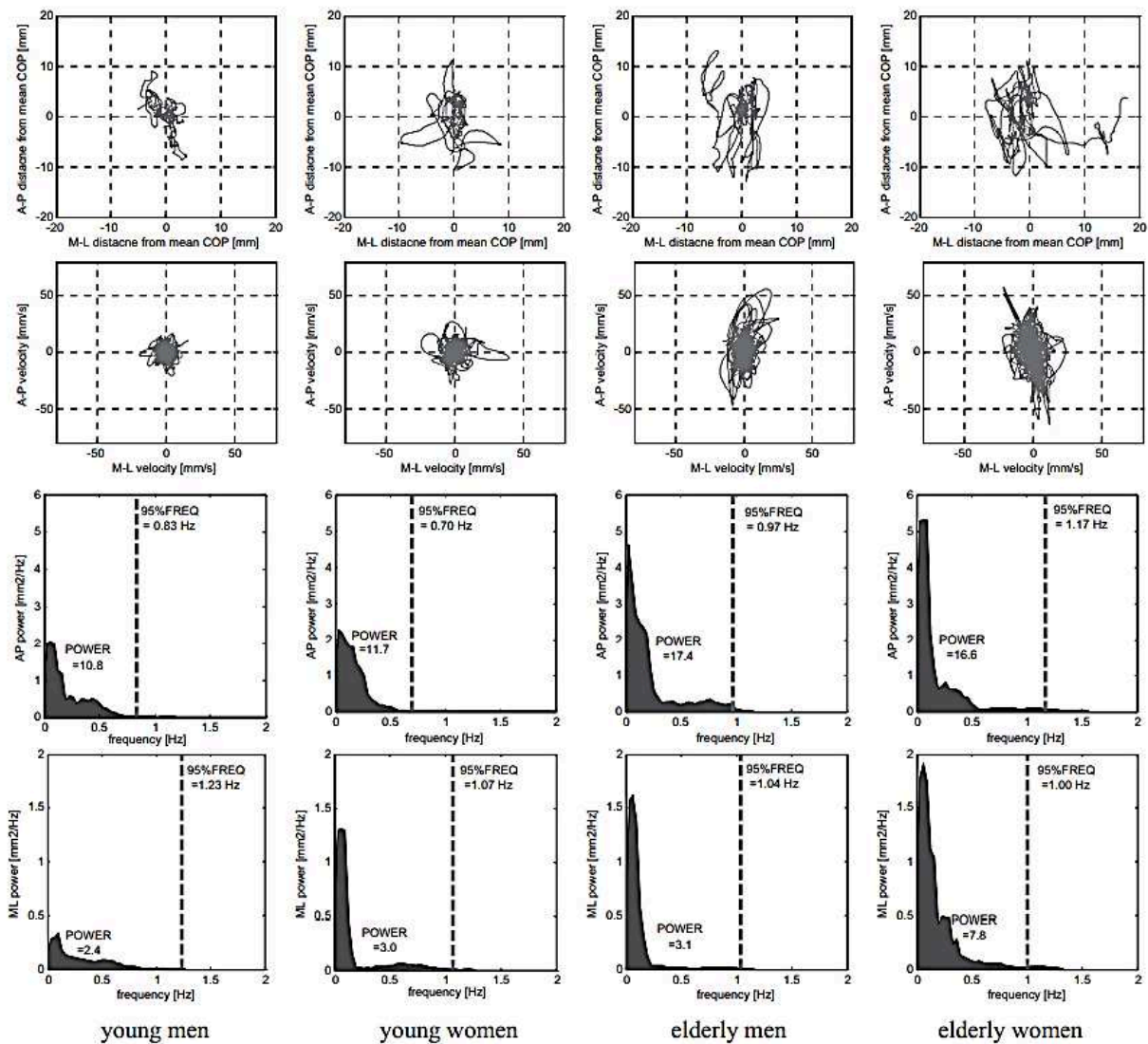


Figure 24: Representative center of pressure (COP) trajectories of distance and velocity (1st and 2nd rows, respectively) and power spectrums in anteroposterior (AP) and mediolateral (ML) directions (3rd and 4th rows, respectively). In the power spectrums, 95% power frequency (vertical dotted line, 95%FREQ) and total power (POWER) are indicated. Columns indicate young men, young women, elderly men and elderly women from left to right. (Kim, 2010)

C.2. Assessments of afferences systems

Evaluating the afference systems involved in static balance refers to assessing the sensory inputs that contribute to an individual's ability to maintain stability while being in a stationary position.

2.1. Visual system

The presented visual environment(target, pattern, etc.) causes a modification of postural responses (Wade & Jones, 1997).

Comparing an individual's ability to maintain balance with eyes open and eyes closed can assess the reliance on visual inputs. Balance may be more challenging with eyes closed due to reduced visual feedback. In fact, instability increases when visual information is removed (a 30% increase in oscillations, particularly in the anterior-posterior axis) (Black et al., 1982). The removal of visual information through closed eyes is easy to perform, making it one of the most commonly

conducted evaluations (Peterka, 2018; Sober & Sabes, 2003; van Beers et al., 1999). The Romberg Quotient(RQ) is a neurological test used to assess an individual's sense of proprioception, balance, and coordination (Diener et al., 1984). It is commonly performed by healthcare professionals. It is calculated by comparing the individual's ability to maintain balance with eyes open to their ability to maintain balance with eyes closed (Equation 1). If there is a significant deterioration in balance and stability when the eyes are closed (compared to when they are open), it can be an indication of impaired proprioception, vestibular dysfunction, or other neurological issues. This test is performed on a force platform so that the RQ is computed as follows:

$$RQ = \frac{CoP \text{ displacement eyes closed}}{CoP \text{ displacement eyes open}} \quad (1)$$

The CoP displacement parameters commonly used are Surface or Length of displacement.

Modifications in the CoP displacement are observed based on the distance between the wall and the participant (Kapoula & L  , 2006) and when a target is presented (Asten et al., 1988; Gautier et al., 2008; L. Nashner & Berthoz, 1978). Introducing visual conflicts or information, such as moving backgrounds, visual illusions or targets, can disrupt the visual system's cues and reveal how well an individual adapts to changing visual input.

A stable visual target can provide a visual reference point that helps stabilize posture. By fixing their gaze on the target, a person can better control their body position. The brain can adjust motor and muscle signals to maintain the desired posture which reduces the movement of the CoP and minimizes oscillations (Laurens et al., 2010). Pictures or images can also impact how the body maintains stability during static standing (Figure 25). A picture with a clear point of reference, such as a horizon or vertical line, can act as a visual anchor. Pictures with visual cues related to depth perception or spatial orientation can influence how the brain interprets the body's position in space.

Dynamic visual input can challenge static balance by introducing moving visual stimuli. They assess an individual's ability to adapt and respond to changing visual cues while keeping their body in equilibrium. It can lead to conflicts between visual and vestibular cues. For example, if a person is fixating on a moving object while standing still, the visual system might detect the movement, leading to postural adjustments. As the eyes track the movement, the body might sway in response, especially if the visual input is faster or more complex. They can induce amplification of postural sway (Laurens et al., 2010).

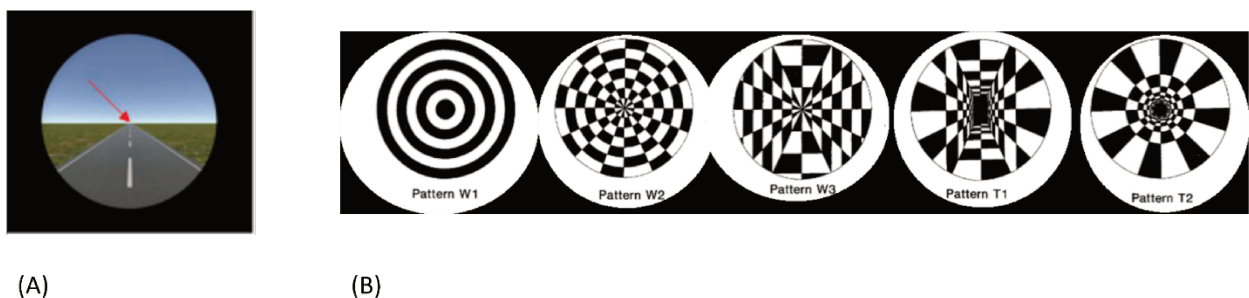


Figure 25: (A) Visual scene displayed on a head-mounted display (Taneda, 2021). (B) The stimulus patterns presented to the subjects (van Asten, 1988)

Optic flow, the apparent motion of objects as we move, can provide cues about the body's movement relative to the environment (Figure 26). Incorporating dynamic visual input can affect how the brain perceives self-motion and adjusts posture accordingly (Raffi & Piras, 2019).

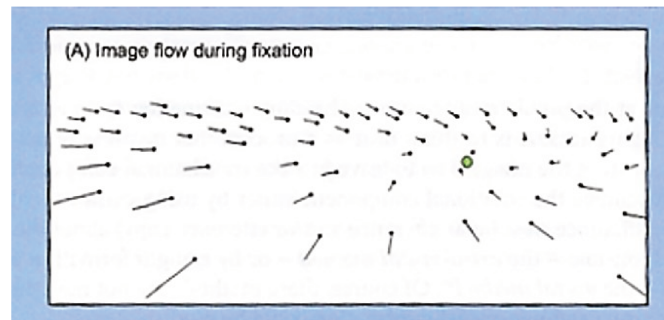


Figure 26: Fixation of a stationary object (green circle) while moving (adaptation from Tresilian, 2012)

Finally, it is usual to evaluate standing balance in a room in front of a wall. The distance from a wall can challenge static balance by altering the visual and proprioceptive cues available to an individual while they maintain a stationary position. Having a wall in close proximity can provide a visual reference point that enhances stability by using the wall as a visual anchor. Standing closer to a wall limits the body's ability to lean or sway in that direction (Kapoula & Lê, 2006). This reduces the extent of somatosensory cues from the proprioceptive system (Figure 27). This decreases the width of the base of support and challenges balance by limiting the body's ability to make subtle adjustments.

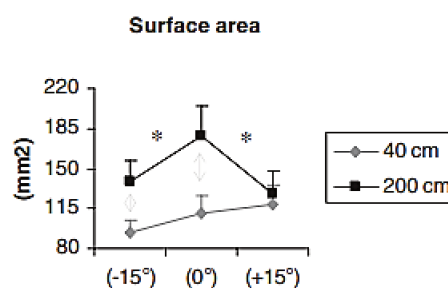


Figure 27: Significant interaction between gaze position and distance to the wall on standing balance: differences between gaze positions (0 vs.15 up and 0 vs.15 down) are significant only for the far distance; the distance effect is significant only for the straight-ahead (0) and the 15 down gaze positions (post hoc test at $p < 0.05$, indicated by double arrows)

2.2. Vestibular system

Specific tests, such as the Romberg Test or Fukuda Stepping Test, can help identify issues related to vestibular dysfunction or impairments (Honaker et al., 2009; Khasnis & Gokula, 2003). To assess the Romberg Test, the patient being tested is asked to stand still with his feet together, arms along the body and eyes open. Then, he is instructed to close his eyes while maintaining this upright position for about 20 to 30 seconds. If the patient loses balance while being eyes closed, this may suggest a vestibular issue (Petersen et al., 2013). To assess the Fukuda Stepping Test, the patient is asked to stand still with eyes closed. Then he is instructed to step in place for about 50 steps (eyes closed). If the patient has no vestibular or balance issues, he should be able to step

in place with little deviation. If the patient drift or rotate to one side, the orientation of the deviation can give insight about the vestibular impairment (Zhang & Wang, 2011).

Controlled head movements (e.g., tilting, nodding) while standing can also assess the vestibular system's contribution to balance control. Gathering information about an individual's history of dizziness, vertigo, or motion sickness can provide insights into potential vestibular problems.

Evaluation on a force platform is mainly a comparison between a vestibular dysfunctional population and physiological population. However, challenging balance control with visual cues or somatosensory modifications can help assess the vestibular system's influence (Di Fabio, 1995).

2.3. Somatosensory system

Sensory manipulation can challenge this system (Shumway-Cook & Horak, 1986). Applying localized vibrations or tactile stimuli to specific muscles or joints while the individual maintains a static stance temporarily disrupt somatosensory feedback and allows to observe the body's responses (Spiliopoulou et al., 2010).

Single-leg stance challenges the somatosensory system by reducing the number of points of contact with the ground. The tandem stance is also more challenging than the baseline assessment (stand barefoot with feet shoulder-width apart and arms relaxed), as feet together. All these positions reduce the size of the BoS (Jeon et al., 2019).

Assessing balance on different surfaces (e.g., firm ground, foam, unstable platform) challenges the somatosensory system and its ability to provide feedback about foot position and pressure (Peterka, 2018).

Reducing somatosensory information can have a significant impact on static balance. When somatosensory cues are diminished, whether through altered sensory conditions or impairments (Lencioni et al., 2015), several balance-related effects can occur. It leads to increased postural sway and can result in an unstable posture, making it more challenging to maintain an upright position (Alexander & Kinney LaPier, 1998; Zarkou et al., 2020). Individuals may rely more on visual and vestibular cues to maintain balance (Sundermier et al., 1996). This shift can lead to sensory conflicts if these systems do not integrate seamlessly (Fabio & Badke, 1991). This can also lead to inaccurate perceptions of weight distribution, potentially causing individuals to shift their weight inappropriately. In this case proprioception, which is closely tied to somatosensory input, becomes compromised (Lao et al., 2008). This can hinder the ability to perceive joint angles and muscle tension accurately. Moreover reduced somatosensory input can impact activities requiring precise balance control, such as standing on one leg, walking on uneven surfaces, or navigating obstacles (Hu & Woollacott, 1994). Aging can lead to a gradual decline in somatosensory function, making older adults more susceptible to balance challenges (Shaffer & Harrison, 2007). It's important to note that the impact of reducing somatosensory information can vary based on factors like the degree of reduction, individual adaptability, and compensatory mechanisms, which are linked to aging or impairments for example (Mahoney & Verghese, 2020; Torre et al., 2013). Individuals with sensory impairments or neuropathies may find it more challenging to participate in balance training or rehabilitation programs.

As static balance is impacted, gait initiation, especially when transitioning from a static to a dynamic state, may be affected due to insufficient feedback about the position and movement of the body (Osoba et al., 2019). This can increase the risk of falls, particularly in environments where surfaces are uneven or unpredictable.

D. Dynamic balance and locomotion

D.1. Definitions, mechanisms and assessment

1.1. Definitions and mechanisms

Dynamic balance refers to the ability of an individual to maintain stability and control over their body while in motion or when subjected to external forces. As you shift your weight and move your body, your balance mechanisms work to keep you upright and steady (Aggarwal & Cai, 1999). In the context of gait, which refers to the pattern of movement during walking, dynamic balance is of paramount importance (Neptune & Vistamehr, 2019). Walking is a complex motor activity that requires coordinated movement of various body segments while maintaining stability and balance (Shimada et al., 2003). The gait cycle is typically divided into two main phases: the stance phase and the swing phase. The stance phase is the period when the foot is in contact with the ground. It makes up roughly 60% of the entire gait cycle and is further divided into several sub-phases (initial contact, loading response, midstance, terminal stance and pre-swing). During the gait cycle, the foot transitions from a heel strike to a toe-off. The swing phase is the period when the foot is not in contact with the ground. It constitutes around 40% of the gait cycle and is also divided into sub-phases (initial swing, midswing and terminal swing) (Tunca et al., 2017) (Figure 28). These phases create a continuous cycle as one leg transitions into the next cycle (Kharb et al., 2011).

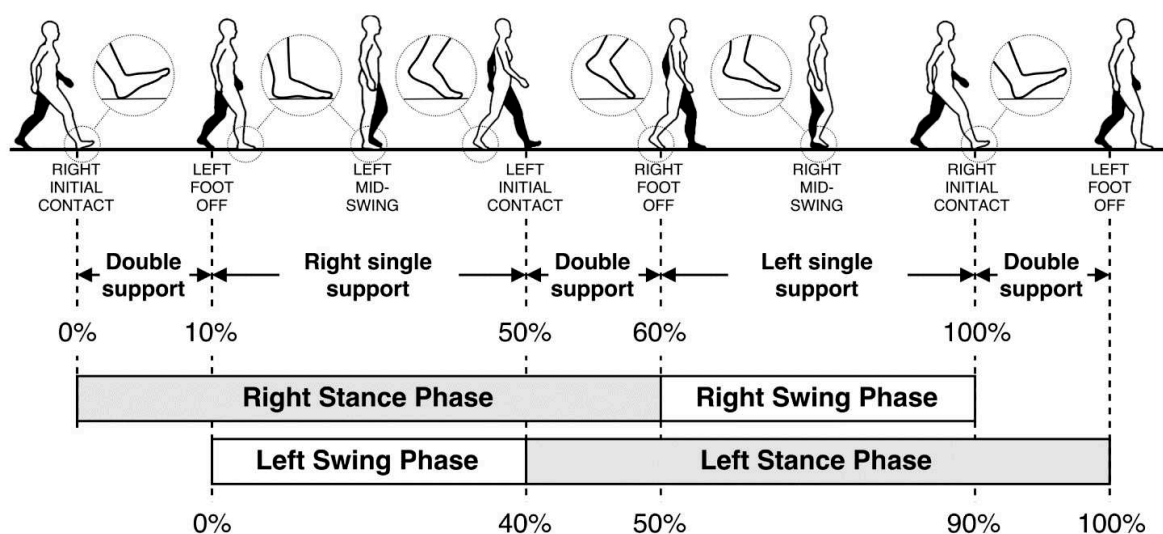


Figure 28: Human gait cycle (Tunca, 2017)

During the gait cycle, there are moments when one foot is off the ground and the body is balanced on the other leg. This is called the single-leg stance phase. Dynamic balance ensures that the body remains stable and centered over the supporting leg during this phase, preventing a loss of balance (Neptune & Vistamehr, 2019; Patton et al., 1999). As said before, the concept of the inverted pendulum is often used to explain and analyze the dynamic balance and stability involved in maintaining an upright posture during the gait cycle (Kuo, 2007). During the stance phase of gait, when one foot is in contact with the ground, the body CoM moves forward. This mimics the idea of a controlled fall of the inverted pendulum. Just like how a controlled force is applied to prevent the inverted pendulum from falling over, our muscles and nervous system make precise adjustments to prevent us from falling while walking. The CoM of the human body is analogous to the pivot point of the inverted pendulum. As the body CoM moves forward, it creates a forward rotation. The timing and placement of each footstep play a role in maintaining stability, much like adjusting the base of an inverted pendulum to keep it upright. The foot's landing point helps to ensure that the CoM remains within a safe range. The swing phase of gait involves moving the leg forward in preparation for the next step. This phase can be likened to the upward swing of the inverted pendulum, where the pendulum moves away from its stable position (Figure 28).

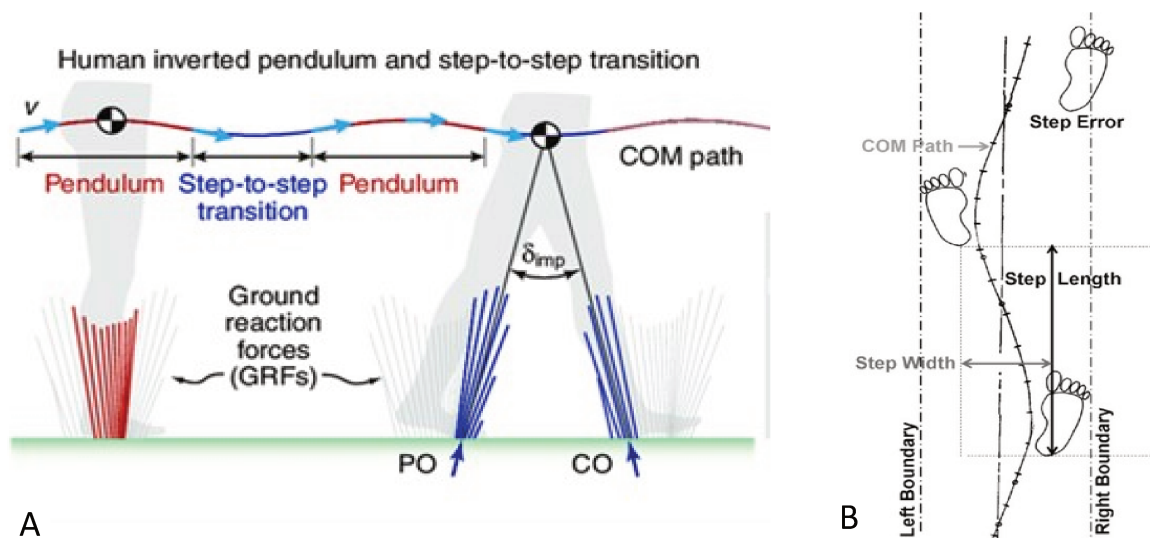


Figure 29: (A) The human CoM moves in a roughly sinusoidal path, which may be divided into inverted pendulum and step-to-step transition phases, corresponding approximately to single and double support, respectively. Ground reaction forces (GRFs) from each leg produce push-off and collision forces (highlighted with thicker lines during double support) that sum to the impulse vectors (labeled PO for push-off and CO for collision) separated by an angle, δ_{imp} . (Adamczyk, 2009). (B) Narrow-base walking task, showing CoM path and the method for calculating step width, step length, and step errors (Kelly 2008).

The CoM follows a distinct pattern as the body goes through the different phases of the gait cycle (Hof, 2008; Tesio & Rota, 2019) (Figure 29). It is a simple way to analyze gait. At the beginning of the stance phase, when the foot makes initial contact with the ground, the CoM begins its ascent in the vertical plane, reaching its highest point during the flat-footed stance. As the body's weight is transferred onto the supporting leg, the CoM starts to descend gradually. The CoM reaches its lowest point around midstance. This is the point where the body's weight is most directly over the supporting foot. Its vertical movement reverses its trajectory and starts to ascend. As the body

moves from midstance to terminal stance, the CoM continues to rise. The weight is shifted toward the forefoot, preparing for push-off. During the pre-swing phase, the CoM experiences a rapid upward movement as the body begins to shift weight to the opposite leg in preparation for the swing phase. As the leg enters the swing phase, the CoM continues its upward trajectory. The opposite leg begins to clear the ground, and the body's weight is primarily supported by the swinging leg. The CoM reaches its highest point during midswing. The body is moving forward, and the swinging leg is at its peak height. As the leg prepares to make contact with the ground, the CoM starts to descend once again. The body is positioned for the next initial contact. The CoM rises and falls as the body's weight is transferred from one leg to the other during the walking cycle: this is the vertical axis movement. It moves laterally from side to side to help maintain balance and ensure a smooth transition between the supporting and swinging legs. The lateral movement of the CoM is particularly important during the stance phase to maintain stability and prevent excessive side-to-side movements: this is the lateral axis movement (Gutierrez-Farewik et al., 2006; C. R. Lee & Farley, 1998; Lugade et al., 2011; Tesio & Rota, 2019). The CoM path during the entire course of movement exhibits specific characteristics, such as a stereotypical locomotor trajectory, indicating common patterns during simple locomotor tasks like walking straight or making a single turn (Pham et al., 2011).

As the process of walking involves coordinated transfer of body weight from one lower limb to the other, dynamic balance plays a crucial role in facilitating the seamless transition of load, thereby mitigating the risk of falls or stumbles during lateral shifts. Dynamic balance, a fundamental concept in biomechanics, denotes the capacity to sustain stability and equilibrium while in motion. Achieving efficiency in this context mandates precise postural control, which, in turn, entails the modulation of muscular tone, articular motion, and body orientation to counteract external forces and uphold the fluidity of movement (Jordan et al., 2007). The orchestration of musculoskeletal coordination and the optimization of muscle strength are further instrumental components of this dynamic balance. Sensory feedback serves as a pivotal mechanism for ensuring accurate responses to perturbations and safeguarding against erroneous adaptations when traversing uneven terrains or encountering obstacles in the environment. The intrinsic capabilities of individuals and the environmental conditions of locomotion affect the gait cycle and, consequently, its parameters (Hernández et al., 2009; Kelly et al., 2008).

Analyzing this gait cycle enables the assessment of a patient's capabilities, which can be done through the analysis of their CoM, for example, or by employing clinical tests.

1.2. Assessment of dynamic balance

To assess gait, various parameters of a person's walking pattern can be evaluated. These parameters highlight the quality of one's gait. Firstly, it is possible to examine CoM motion and its symmetry during repeated walking phases, facilitating the assessment of dynamic balance (Akhtaruzzaman et al., 2016; G. F. Harris & Wertsch, 1994). The CoM path or trajectory also gives insights on the gait quality. Additionally, one can analyze spatial parameters, encompassing step and stride length, step width, and lower limb joint kinematics (e.g., ankle and knee). Spatiotemporal parameters also offer valuable insights into gait quality. Quantifying metrics such as walking speed, stance and swing phase durations, cadence, double support time, single support time, and heel-to-toe pattern is possible. Furthermore, a comprehensive assessment of muscle

activity and kinetic parameters can yield additional valuable information about the biomechanics of walking. These quantifications require tools such as force or pressure platforms, motion capture systems, cameras, and electromyography (EMG). Motion capture systems can track the movements of reflective markers placed on the body to create a detailed three-dimensional analysis of gait (and the CoM computation) (Pfister et al., 2014). This can provide information about joint angles, stride length, step width, and other parameters related to dynamic balance. Force or pressure platforms are devices that measure the forces the moment, or the repartition of pressures, exerted by the feet during walking (Klöpfer-Krämer et al., 2020; White et al., 1999). They can provide data on the distribution of forces, the timing of weight transfer, and the stability of the center of pressure as it moves through the gait cycle. Wearable sensors, such as accelerometers or gyroscopes, can provide real-time data on gait patterns, step characteristics, and balance during walking.

The implementation of such devices and the processing of the measured data do not always allow for their optimal use in a clinical setting. New technologies bring forth new, user-friendly and tools and more environmentally friendly (Davis et al., 1991; T. Liu et al., 2009; Tong & Granat, 1999; Whittle, 1996).

There are other ways to assess gait besides analyzing the CoM and cameras or EMG data. Clinicians can visually observe a person's gait to identify any abnormalities, asymmetries, or deviations from a typical walking pattern. This might include looking for uneven weight distribution, changes in arm swing, or excessive body sway. The TUG (Timed Up and Go) test involves timing how long it takes for an individual to stand up from a chair, walk a short distance (usually around 3 meters), turn around, return to the chair, and sit down (Bohannon, 2006; Savva et al., 2013).

To assess gait and dynamic balance, multisensory integration must also be taking into account. It plays a significant role in gait control and balance (Takakusaki, 2017). It involves the brain's ability to combine information from different sensory modalities, such as vision, somatosensory information, and the vestibular system, to create a coherent perception of the environment and one's own body movement. This integration is crucial for maintaining stability and adjusting movements (Perrin et al., 2009). Vision provides essential cues about the environment, such as obstacles, terrain changes, and the position of nearby objects. Visual feedback helps adjust step length, foot placement, and balance during gait (Campos et al., 2012). The vestibular system detects changes in head position and angular motion, providing information about head orientation and movement in relation to gravity. This information helps adjust the body's posture and movements to stay upright and maintain equilibrium. Proprioceptive sensors in muscles, tendons, and joints provide information about the position, movement, and tension of body parts. This sensory input contributes to maintaining proper joint angles and muscle activation during walking. Tactile and pressure sensations on the skin provide additional information about the contact between the feet and the ground. These sensations help adjust gait patterns to adapt to different surfaces and conditions. Multisensory integration ensures that humans can move efficiently and maintain balance, adapting to different environments and conditions (Ricotti, 2011; Wegener et al., 1997).

D.2. Assessments of afferences systems

2.1. Vestibular system

By observing and analyzing a population with a vestibular deficit and comparing it to a healthy population, it is possible to evaluate the impact of this system on gait. It contributes to spatial orientation, gaze stabilization, postural adjustments and spatial navigation.

A vestibular perturbation is going to modify gait pattern by abnormal trajectories or difficulties to maintain head-pitch movement if no visual information given for example (Kennedy et al., 2003; Lang et al., 2013). The gait impairment is linked to the vestibular disease. To assess this system, man can also do a galvanic vestibular stimulation which influence the firing of vestibular nerves and, in turn, affect the signals sent to the brain related to balance and spatial orientation. With unilateral stimulation, the gait pattern is laterally deviated. Patients may present variations in their spatiotemporal or spatial parameters of walking (less speeding or stride time, deviation of trajectories, ...) (Devèze et al., 2015).

2.2. Visual system

The evaluation of visual information during gait involves assessing how visual cues influence a person's walking patterns, balance, and overall movement. Visual information is a key sensory input that helps individuals navigate precisely their environment, avoid obstacles, and maintain stability during walking (Marigold & Patla, 2008; Pham et al., 2011).

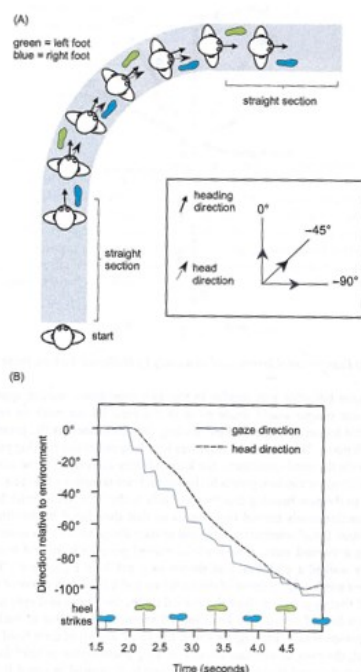


Figure 30: Experimental layout(A) and results (B) from a study by Imai et al. 2001) (Tresilian, 2012)

Where a person is looking, plays a significant role in gait control and balance (Figure 30). Gaze provides visual feedback about the environment, obstacles, and potential hazards. By looking ahead, individuals can anticipate changes in terrain and adjust their steps to avoid obstacles and uneven surfaces., or judge distances (Dokka et al., 2011; Pradeep Ambati et al., 2013). It helps individuals maintain spatial orientation by providing visual references in the environment.

Looking at distant objects can help orient the body in space and maintain a sense of direction during walking. Gaze fixation on a stable point can assist in balance control. Focusing on a stable reference point helps individuals maintain an upright posture and steady their head movements during walking. The vestibulo-ocular reflex (VOR) stabilizes gaze by moving the eyes in the opposite direction of head movements to maintain a stable view.

Walking eyes closed allow individuals to visualize the impact of visual information (Kennedy et al., 2003). When your eyes are closed, you rely more on proprioceptive and vestibular cues to maintain stability. Stride length, step width, and the overall fluidity of movement can be affected as your body adapts to the lack of visual information. It increases body sway. This is due to the CNS's reliance on other sensory inputs to maintain balance. This is the simplest way and a very common way to evaluate visual role on gait. Perturbing the visual information is also possible by wearing specific glasses (Perry et al., 2001) or a trial frame (Timmis et al., 2015). These visual modifications imply gait adaptation such as higher lift of their foot, or delay in initiation of termination gait.

Analyzing visually impaired population can also give insights into the visual role during gait (Halleman et al., 2010; Nakamura, 1997). Parameters like stride length, time of stance, walking speed are impacted (Figure 31).

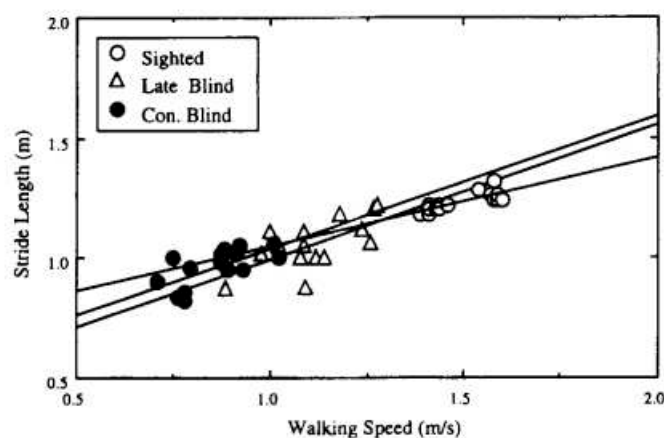


Figure 31: Scatterplot of correlations between walking speed and stride length in late blind ($r = 0.652$, $p < 0.01$), congenitally blind ($r = 0.675$, $p < 0.01$) and sighted persons ($r = 0.793$, $p < 0.01$).

2.3. Somatosensory system

Somatosensory evaluation during gait involves assessing how the sensory receptors in muscles, joints, and skin contribute to balance, proprioception, and overall movement control while walking.

Applying low-frequency vibrations to specific muscles or joints during gait can temporarily interfere with somatosensory input. Observing how individuals adapt their gait in response to these vibrations can provide insights into the role of proprioception. EMG can assess the function of peripheral nerves and muscle activity. Applying gentle touch or pressure to specific areas of the foot can alter somatosensory input and impact gait patterns.

A proprioceptive stimulation induced by a foot movement (Podokinetic stimulation) provokes a modification of the locomotion trajectory stereotypy (Earhart et al., 2002)

Researchers can manipulate the somatosensory input by altering the surface conditions (e.g., walking on foam or uneven surfaces) or providing additional sensory cues (e.g., using textured insoles). These manipulations can help assess how somatosensory information influences gait adjustments. Dynamic balance is especially important when walking on uneven or unstable surfaces. It enables individuals to adapt their movements and make rapid adjustments to maintain stability and prevent falls. It also involves the coordination of the arms and upper body as well.

E. The foot case

Evaluating the impact of the feet and its characteristics on static and dynamic balance involves assessing how the sensory cues and movements of the feet contribute to maintaining stability.

Sensory manipulation of the foot involves introducing controlled stimuli to specific areas of the foot. The manipulation can be either a stimulation or an inhibition.

Stimulations are vibrations or mechanical. Localized vibrations permit to apply gentle vibrations to different parts of the foot. During a static task, vibrations impact CoP parameters by reducing its area or length (Schlee et al., 2012). If the vibration is applied on specific area like laterally under one foot, the CoP shifts in the opposite direction (Kavounoudias et al., 1998). Foot vibration also induce modification of gait pattern (Yamashita et al., 2021). It induces a reduction of the gait cycle duration or the stride length. It also has an impact on the foot trajectory probably related to the modification of lower limbs kinematic. Tactile stimulation can be created using textures or materials variations (e.g., soft foam, rough surfaces). It can be insoles, textured insoles (Christovão et al., 2013; Maurer et al., 2001).

It is also possible to reduce the information or analyze a population with peripheral neuropathy, such as diabetes (Kars et al., 2009; Meyer et al., 2004; Paton et al., 2016). One way to reduce information is anesthesia either invasive or not. Anesthesia of the foot sole means a lack of sensation or feeling in that area. This loss of sensation affects the ability to perceive touch, pressure, and other sensory cues from the ground, making it challenging to sense the body position and make appropriate adjustments for balance. It presents challenges due to the need for either invasive procedures or prolonged and intricate protocols to maintain consistent sensory inhibition throughout the experiment within and between participants (Magnusson, Enbom, Johansson, & Pyykkö, 1990; Magnusson, Enbom, Johansson, & Wiklund, 1990; Meyer et al., 2004). The foot anesthesia also induce modification in gait analysis. It shows that the foot cutaneous receptors play a role to inform the SNC about location of the foot, or participate to slowing process (Perry et al., 2001).

One of the most used tools is the foam pad to assess somatosensory influence on balance control. The foam pad is made of an unstable and padded surface designed to create an unstable environment. The participant is asked to stand on the foam pad while maintaining balance. This is analyzed with the CoP measurement between conditions. This challenges the body's ability to maintain balance due to the constantly shifting and unstable surface (Mancini & Horak, 2010; L. M. Nashner, 1982; Sober & Sabes, 2003). The plantar quotient(PQ) is a measure that assesses the

difference in CoP movement when a person is standing on an unstable surface (like foam) compared to a stable surface (like a hard floor).

It can be done with length, area, and velocity of CoP . Its formula is (Equation 2):

$$PQ = \frac{\text{CoP Length on foam pad (mm)}}{\text{CoP Length on hard ground (mm)}} \quad (2)$$

Thicker foam pads make the task more challenging, while thinner ones are used to evaluate plantar information and offer less ankle proprioception compared to thicker foams (Bisson et al., 2014). However, it is essential to note that no foam pad has been validated as a gold standard for balance assessment. Various foam types are available, and their thickness and hardness significantly impact balance control (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; B. Liu et al., 2018; Patel et al., 2008). Clinicians have a wide range of foam choices, leading to variability between patients and clinicians, making it difficult to compare diagnoses or draw uniform conclusions. A non-physiological response on thin foam pad could indicate a different integration of foot information. Typically, a foam pad presents a challenge to balance control. If a patient exhibits greater stability on the foam pad compared to the floor, it may indicate a podal inefficiency, leading to different posture reactions when using foot orthoses (Foisy & Kapoula, 2017). This can imply a therapeutic choice in foot orthoses treatment.

Foot orthoses are multiples and their choice are patient or pathology dependent (Bonanno et al., 2017). They are custom made by podiatrists. Materials and shapes are multiples with specific properties (elasticity, density, thickness, ...) (Figure 32). Custom-designed foot orthoses can redistribute pressure across the foot. Balanced pressure distribution can contribute to better stability during static standing. Insoles with features like heel cups, arch support, and metatarsal pads can improve overall foot stability. A stable foot can better support the body's weight and minimize the need for constant adjustments to maintain balance. Some insoles are designed with sensory elements that stimulate the receptors. This enhanced sensory feedback can improve proprioception, making individuals more aware of their body position and allowing them to make subtle adjustments to maintain balance (Christovão et al., 2013; Palluel et al., 2008; Perry et al., 2000; Roll et al., 2002).



Figure 32: different type of orthopedic insoles or inserts (shape, size, material) (www.flexor.es)

Insoles that promote a more aligned posture can indirectly impact static balance by reducing unnecessary postural adjustments during standing. It's important to note that the impact of insoles

on static balance can vary from person to person. Factors such as individual biomechanics, foot structure, and any existing conditions should be considered when assessing the effects of insoles on balance. In fact, insole insert does not always produce the same effect on individuals.

Arch support, as an example, will support medium foot and have an impact on foot and ankle proprioception feedback. Insoles impact foot alignment which influences dynamic balance. However, studies focus on different insoles with multiple objectives and on patients. Some insoles include thin elements (few millimeters) to stimulate area from the foot (Chen et al., 2014). Based on the effect of an electric stimulation, they are said to have the same impact. EMI® (medio-intern Element) is one of them (Figure 33). This element is placed under the foot arch. Few studies worked on those. One can observe a contralateral shift of the CoP when the element is positioned under the foot. This result was obtained from a small population of adolescents. An analysis on a larger cohort is necessary to validate the result and better understand the functioning of the element (Janin & Dupui, 2009).

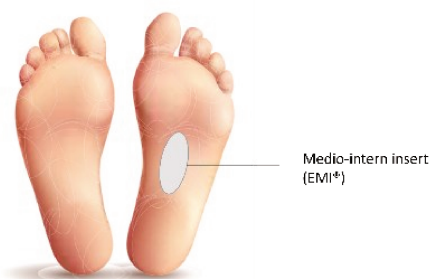


Figure 33: Medio-intern Element (based on Janin, 2009 and Foisy, 2017)

Textured insoles can also stimulate foot receptors and have an impact on static and dynamic balance (Alfuth, 2017; Hatton et al., 2009, 2012; Ma et al., 2016; Wilson et al., 2008). The heightened sensory input from textured insoles can lead to greater activation of the muscles responsible for maintaining balance. Muscles in the feet, ankles, and lower legs are engaged more actively to respond to the sensory feedback, leading to improved stability. This increased sensory information allows the brain to make more precise adjustments to maintain an upright posture (Kenny et al., 2019). The textured surface of the insoles stimulates the proprioceptive receptors in the feet which leads to a specific activation of lower limb muscles (Robb & Perry, 2022).

This can lead to improved balance responses during gait (Aruin & Kanekar, 2013). Individuals may make subtle adjustments in their gait pattern by taking shorter steps or modifying their stride to accommodate the sensory feedback.

On the other hand, walking on a compliant surface challenges dynamic balance. The proprioceptive adaptation is on the lower limb joints (hip, knee and ankle). Gait pattern and CoM motion are modified by compliant surfaces (MacLellan & Patla, 2006) to allow CNS to maximize stability. Uneven fields induce a biomechanical adaptation of gait pattern (Voloshina et al., 2013).

Conclusions about static and dynamic balance are therefore difficult to generalize (Christovão et al., 2013; Lourenço et al., 2013) due to difference on foot orthoses or populations.

Synthesis and objectives

In the field of biomechanics and podiatry, the foot, equipped with its array of skin sensors, plays a pivotal role in providing vital information regarding the nature of the surface upon which an individual stands or moves (Shumway-Cook & Woollacott, 2007). The ability to maintain effective postural control and dynamic stability is paramount for performing routine activities of daily living. The utilization of orthopedic insoles represents a viable strategy to enhance postural and dynamic control by rectifying deviations and stimulating specific areas to induce beneficial modifications. However, a crucial question emerges: How can we systematically evaluate the capacity of the plantar system to efficiently integrate the sensory input it receives?

The assessment of plantar sensory information can be undertaken through various methodologies. Traditionally, for the quantification of this system's impact on postural and motor control, a foam pad is interposed between the feet and the supporting surface. The perturbation induced by this foam pad is assessed by analyzing the CoP displacement. This perturbation, in essence, challenges the sensory-motor system, engendering an instability (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; Preszner-Domjan et al., 2012). Regrettably, there is a lack of a universally recognized gold standard test protocol in this context. While the positioning of subjects and instructions have been relatively consistent across the literature (e.g., feet placed at a 30° angle, fixed gaze, arms at the sides, and data recording for a duration of 30 seconds), there exists significant variability in the choice of foam materials among different studies. Furthermore, specific thickness recommendations for the foam pad are noticeably absent, despite the incontrovertible fact that this parameter profoundly influences postural responses and center of pressure kinematics. Moreover, intrinsic material characteristics often remain unspecified or vary across investigations. Alterations in material hardness have been demonstrated to elicit discernible effects on subject responses during static tasks (Boonsinsukh et al., 2020; Patel et al., 2008). Thus, the establishment of precise standards for evaluating plantar sensory integration within a healthy population is imperative. This standardization will facilitate the identification of subpopulations manifesting atypical responses.

Additionally, the thickness of the foam pad has been identified as a significant factor influencing the proprioceptive system's activity (B. Liu et al., 2018). Consequently, evaluating the plantar cutaneous system in isolation is deemed unfeasible. Nonetheless, minimizing proprioceptive stimulation presents an avenue for optimizing the utilization of other sensory systems engaged in postural control. By exclusively modifying the assessment through the utilization of a foam pad, it becomes possible to accentuate the visualization of the influence exerted by the plantar cutaneous system and its amalgamation into the broader framework of motor control. Nevertheless, the selection of appropriate foam materials is a daunting task due to the myriad of

options available, rendering it challenging to justify choices (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; Patel et al., 2008). Consequently, the acquisition of more detailed data concerning these materials is imperative to enable informed decisions. The selection of a thin foam pad thickness is particularly driven by the objective of obtaining a specific evaluation of the somatosensory system while aligning with current podiatric practices (Foisy & Kapoula, 2017). Notably, practitioners in France commonly employ foam pads with thicknesses on the order of a few millimeters when assessing the integration of plantar sensory information.

The integration of visual information represents an additional facet worthy of exploration. Visual information presented to participants has been demonstrated to exert a profound influence on postural control (Kapoula & Lê, 2006; Raffi & Piras, 2019; Taneda et al., 2021). For instance, the "eyes closed" condition, extensively documented in the literature, leads to a significant increase in center of pressure oscillations, approximately 30%, when compared to the "eyes open" condition (Abrahamová & Hlavačka, 2008; Black et al., 1982). However, it is crucial to acknowledge that factors such as the presence of a visual target, the nature of the target, or its distance from the participant can introduce distinct modifications in postural control (van Asten et al., 1988). Consequently, inadvertent provision of visual information, such as posters or paintings within the testing environment, may yield disparate results among practitioners. Therefore, a comprehensive understanding of these modifications and their implications is paramount for the standardization of testing procedures.

Upon obtaining results in a controlled environment involving the use of a foam pad, the concept of a "plantar quotient" emerges as a valuable metric. This quotient expresses the ratio of the modification in CoP displacement induced by the foam pad disturbance (Foisy & Kapoula, 2017). Consequently, it serves as a quantifiable indicator of the foam's impact on static postural control, analogous to how the Romberg quotient signifies visual modification (eyes closed) in comparison to the control condition (eyes open). These quotients enable a structured analysis of the perturbation's magnitude. It is conventionally posited that when the plantar quotient falls below unity, it signifies a deviation from physiological plantar integration. Thus, the establishment of norms within the healthy adult population will serve to define finer benchmarks for this ratio. Should this integration be deemed non-physiological, one can reasonably anticipate differential outcomes upon the implementation of an orthopedic insole.

Moreover, Foisy & Kapoula (2017) discusses a modified integration of plantar information when an orthopedic insole is introduced, based on the results of the plantar quotient. However, the highly specific visual information provided to participants in this study raises pertinent questions. If we exclusively consider the modification of plantar sensory input through the medium of a foam pad, does the plantar quotient indeed reveal an altered capacity to integrate the presented information? Furthermore, can the results of the plantar quotient be leveraged to fine-tune orthopedic treatment modalities or evaluate their efficacy?

Lastly, it is imperative to acknowledge that the analysis of the plantar quotient and its association with orthopedic insoles has predominantly been conducted within a static framework. However, the exigencies of everyday life invariably entail dynamic movement, particularly during locomotion. Various methodologies exist for the analysis of human gait. The assessment of CoM displacement offers insight into the subject's trajectory. In straightforward locomotor tasks such as linear walking or singular turns, a discernible stereotypical trajectory emerges. Intriguingly, the

withdrawal of visual information deviates this stereotypical orientation, leading to a reduction in the precision of center of mass (CoM) trajectory. It is noteworthy that orthopedic insoles impart sensory information to the plantar system during each stance phase of the gait cycle.

In conclusion, we have highlighted the multifaceted considerations surrounding the evaluation of the plantar sensory system, particularly in the context of orthopedic insole interventions. It emphasizes the need for standardized assessment protocols, the quantification of sensory perturbations through indices like the plantar quotient, and the recognition of the interplay between sensory modalities, including visual information, in shaping postural control. Furthermore, it underscores the necessity of extending such assessments beyond static conditions to encompass dynamic locomotor scenarios, thereby affording a more comprehensive understanding of the intricate processes underpinning human posture and movement control.

The primary research objective is to systematically acquire normative data characterizing the modifications induced by the application of a thin foam pad on a cohort of healthy subjects. The acquisition of these normative benchmarks serves the fundamental purpose of enabling the identification of atypical responses. This objective seeks to discriminate individuals who manifest minimal postural perturbation as well as those who exhibit pronounced postural fluctuations in response to the foam pad intervention. The overarching aim is to gain insights into the extent to which individuals rely on their plantar sensory input for the maintenance of postural equilibrium.

The second objective entails a systematic exploration of how alterations in visual information provision introduce perturbations in static postural control. This line of inquiry holds pivotal significance for the standardization of assessment protocols and aims to elucidate the potential influence of the visual environment on the observed modifications induced by the foam pad. Specifically, it seeks to identify the specific alterations in visual cues that disrupt static postural control, thus contributing to methodological refinement.

The third objective revolves around the evaluation of whether the plantar quotient, a quantified metric reflecting the influence of the foam pad on static postural control, can function as a predictive tool for the integration of podal sensory information, including the effects of orthopedic interventions like insoles. This objective involves the deliberate selection of participants exhibiting divergent outcomes in terms of their plantar quotient responses. By doing so, it seeks to elucidate whether individuals with varying plantar quotient results also manifest differential responses to the integration of orthopedic interventions. This assessment encompasses both static postural conditions and dynamic locomotor tasks.

In summary, this research endeavors to advance our understanding of the intricate interplay between sensory input, with a specific emphasis on the plantar system, and visual information in shaping static postural control and locomotion within a healthy population. The establishment of normative data, exploration of visual perturbations, and evaluation of the predictive potential of the plantar quotient collectively contribute to a comprehensive scientific comprehension of these intricate interactions. Furthermore, the findings may have practical implications for the design and customization of interventions, such as orthopedic insoles, aimed at optimizing postural control and locomotion across diverse populations. The research outcomes will contribute to the development of a standardized protocol for the assessment of plantar sensory information in static

conditions. This will facilitate improved longitudinal patient tracking over time and enhance the comparability of results across different practitioners.

Chapter 2: Evaluation of plantar function and its interaction with visual cues

This chapter will consist of three studies aimed at analyzing the assessment of plantar cutaneous information through the interposition of a foam pad under the feet and the impact of visual information and the environment on this assessment.

Study 1: Foam evaluation

A. Introduction

In the context of podiatry, the therapeutic objective can encompass multiple aspects when evaluating plantar information. For example, it serves to determine the presence of peripheral neuropathy. Our objective is closely related to the use of orthopedic insoles. Assessing the functionality of thermoreceptors and nociceptors is not the focus of this analysis. Our goal is to determine if the capacity of plantar mechanoreceptors can be evaluated and linked to a specific integration of orthotic information. Therefore, our interest lies in the assessment of mechanoreceptors. Laboratory evaluations such as Neuromicrography are available, but we have chosen to work with clinical tests to provide information and tools to therapists (Strzalkowski et al., 2018).

The clinical tests employed enable an assessment of the functioning of mechanoreceptors. Discrimination testing is one such test, providing insights into the ability to discriminate between two points on a tested skin area. These clinical tests are performed while the subjects are seated and do not allow visualization of integration dysfunction with the postural control system. To conduct this evaluation, practitioners use foam pads. With this interposition, plantar skin receptors perceive less precise information due to the compliance of the surface to the ground. This compliance leads to surface indentation when the subject's weight is applied. This indentation disrupts the equilibrium system, which readjusts to correct posture and maintain balance. Depending on the disturbance's magnitude, the various systems involved will also provide information about the degree of change compared to the initial situation, allowing for a response adjustment. Therefore, the choice of foam is crucial. Its characteristics can cause varying degrees of involvement of these related systems. It is not possible to eliminate the information provided by the vestibular system or proprioceptive system. However, using a thick foam with high compliance will result in greater sinking upon the subject's positioning, leading to an increase in center of pressure displacement induced by the subject's swaying movements. Consequently, the

proprioceptive system will be more alert, increasing its involvement in static control regulation. The same applies to the vestibular system, with an increase in oscillations. Using a thin foam is a solution to minimize the involvement of other systems, effectively "isolating" the plantar skin system as much as possible.

Defining what constitutes a "thin foam" is abstract and must be contextualized within the proposed exercise and chosen population. As mentioned earlier, the multitude of choices makes inter-study comparisons complex. To facilitate comparisons with other data, we have chosen to use a foam already studied in the literature (Dujols, 1991; Foisy & Kapoula, 2016, 2017): Dépron®, which measures 6 mm in thickness. However, it is not a foam used in podiatry but in construction. It does not possess high elasticity, and the compression induced by an individual's weight is maintained even without added mass. Therefore, it is not reusable. It would be interesting to find a reusable foam for ecological purposes that induces the same effect on static balance.

Regarding visual information, similar to foam, the characteristics used for the visual environment in the literature are varied. The distance to the wall is often not specified, nor is the quality of the wall. When a visual target is positioned, its shape or texture is not consistently reported. However, all these parameters affect the subject's stability. To enable comparisons with real-life situations, two visual conditions seem justified: an "eyes open" condition and an "eyes closed" condition. The control situation, which corresponds to everyday life and is also found in the literature, is a situation where the subject stands without any modification of information from any of the systems. "Eyes open" without a foam pad is considered the neutral state. The removal of visual information coupled with the disturbance caused by the foam pad would thus normally be the most disruptive situation in the proposed conditions, in contrast to the control situation.

The primary objective of this study is to establish oscillation norms for healthy adults when subjected to a thin foam pad. This analysis aims to elucidate the physiological adaptation of adults in response to this perturbation, specifically examining how their bodies react and maintain static balance in this specific situation.

A secondary objective of this study is to investigate an ecologically friendly alternative to the foam typically used in the literature, Depron®. To achieve this, we will compare the results of participants when they are exposed to other compliant surfaces of the same thickness. This comparison is intended to determine if alternative materials can be used in place of Depron® without compromising the validity of the study's findings.

B. Materials and methods

B.1. Participants

132 healthy adult participants (57 men, 74 women) volunteered for this study and gave their informed consent. They were 28.7 ± 9.1 y. o, 173 ± 9.4 cm tall and weighed 68.5 ± 11.9 kg. As we aimed at establishing a PQ norm, the sample size was based on studies which determined Romberg quotient norms (Black et al., 1982). Participants should not have any balance disorders (inner ear, vision) and be taking any medication that can disturb balance. They must not have undergone a recent trauma of the lower limbs (less than 3 months or in the course of

rehabilitation). If needed, their visual correction was worn. Pregnant women and elderly people (age above 59 years) were not included. Previous works showed that such population have an altered or different postural control. Participants received an information leaflet and signed an informed consent document validated by the local ethics committee of Rennes 2 University (n°2021007).

B.2. Experimental design

• Foam choice

Our study aims at comparing postural control considering clinically used and reusable foams with Depron® which was initially used to compute PQ ratio. The Depron®, is 6mm thick then we selected 2 foams with similar thickness: Plastazote® and Orthomic® that are traditionally used in clinical practice and reusable. . In addition, an indentation test was carried out at the LGCGM laboratory (Laboratoire de Génie Civil et Génie Mécanique¹) to assess foam properties more precisely. The indentation test characterizes a material resistance to penetration by a penetrator called an indenter. The indentation test was carried out using a spherical indenter with a diameter of 2.5 mm, applying a maximum load of 1N to the Orthomic® and Depron® foam samples, and 0.5N to the Plastazote® sample (Figure 34).

Foam density is the mass of material contained in one cubic foot. As Plastazote® is not as dense as Depron® and Orthomic®, the results of the indentation test are compared at a load of 0.5N. It should be noted that, for the same load, the lower the indentation, the more resistant the material is to penetration. The stiffness of the material is quantified by the modulus of elasticity, which can be obtained by indentation using the beginning of the unloading curve. For the purposes of this study, we limit ourselves to noting that Orthomic® foam has the indentation behavior closest to that of Depron®.

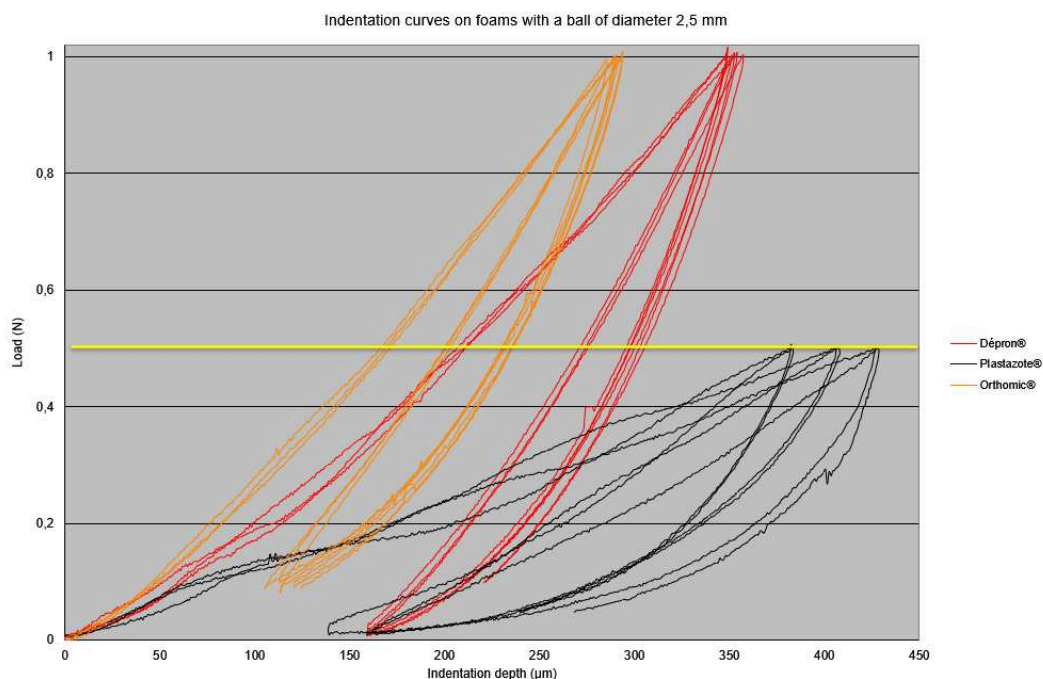


Figure 34: Indentation curves for the 3 foams used in this study.

¹ Civil and Mechanical Engineering Laboratory

Here are the characteristics of the 3 foams chosen (Table 3):

Table 3: Foams parameters

FOAM	Thickness (mm)	Indentation depth (μm) for 0.5N applied)	Relative Density	Hardness (shore A)
Depron®	6	210	40	/
Plastazote®	5	405	70	25
Orthomic®	5	166	270	40

- **Instrumental**

Stabilometry platform

In order to measure CoP position over time, we used the stabilometry platform Fusyo from Medicapteur® (France) (Figure 35). It has a wedge to normalize the position of the feet, with an opening angle of 30°.



Figure 35: Stabilometry platform (Fusyo by Medicapteur®)

Two-point discrimination test

We used a 2-point discrimination disk (Baseline®) to evaluate the participants' capacity to distinguish two applied points on their foot skin and evaluate their sensory perception. The threshold was between 1 millimeter to 2 centimeters (Figure 36).

Sat and eyes closed, participants had to answer either 1 or 2 points were applied on their skin. Five areas were tested: big toe, 1st, 3rd and 5th metatarsal heads, and middle of the heel, which are areas in contact with the ground while standing). The examiner began with the biggest threshold (2cm) and diminish until the participants can't find the good answer 3 times in a row (meaning they were feeling one point instead of 2).

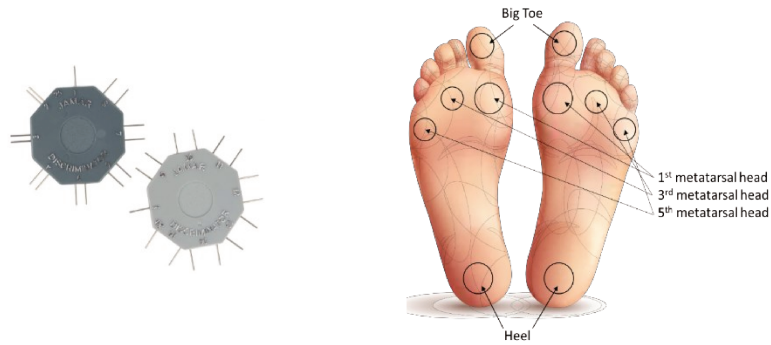


Figure 36: 2 points discrimination disks (Basline®) used in the protocol and the 5 areas tested on participants.

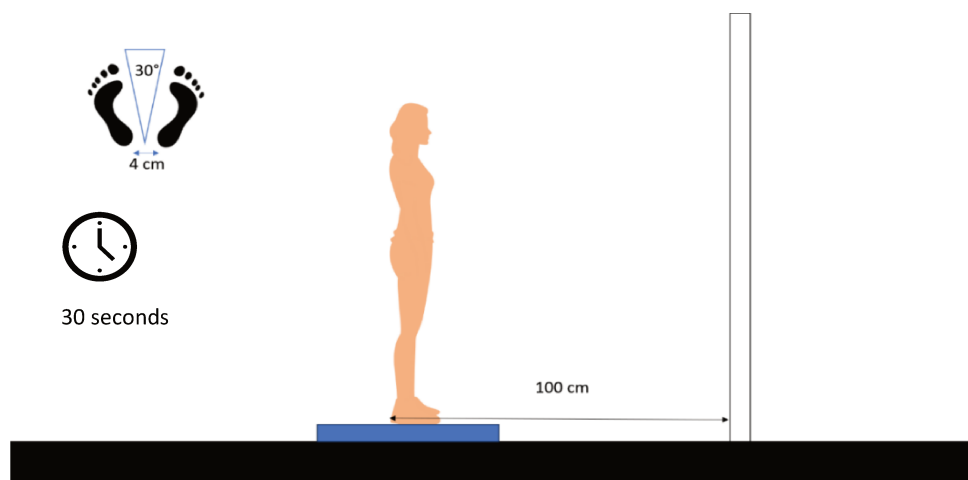
- **Environmental conditions**

The stabilometry platform was placed in front of a white wall with no more visual information. The heels of participants were 100 cm from the wall. The choice of 1 meter was made to avoid distinguishing vertical and horizontal information in the room, such as wall-ceiling junctions. Since the study's goal is the evaluation of plantar information, no specific target was placed in front of the individual's gaze, providing no additional information other than the smooth white wall. The "eyes closed" condition also maximizes the use of the system's information. The room was quiet during recordings.

The experimentation took place in the podiatry clinic of IFPEK (Institut de formation en podologie, ergothérapie et kinésithérapie de Rennes, France)².

- **The static task**

The participants were asked to stand as still as possible for each trial. One trial was 30 second long. Their feet were 30° opened with 4 centimeters between their heels. Their arms along the body. No voluntary movement or speaking was allowed during the recording of a trial. They were asked to look in front of them and make no voluntary eyes movement. They were bare foot(Figure 37).



² Training Institut in Podiatry, Physiotherapy and Occupational Therapy

Figure 37: Illustration of the standing balance task characteristics.

- **Design**

The 2-points discrimination test was performed first, on each foot, for the 5 areas selected. Then the standing balance tasks were performed.

For the static evaluation, we used a repeated measure design. We considered the following factors (Figure 38):

- Foam (4): control condition (no foam), Depron®, Orthomic® and Plastazote®. Foams were located on the stabilometry platform.
- Vision (2): eyes closed or open

A condition corresponded to a combination of the different levels of the foam and vision factor. Three trials were performed for each condition. Between each trial, a rest time of at least 30s was imposed. In total participants performed 24 trials (3 repetitions * 2 vision * 4 foams), in a randomized order. A session lasted between 45 to 60 minutes. Foams were changed between each trial.

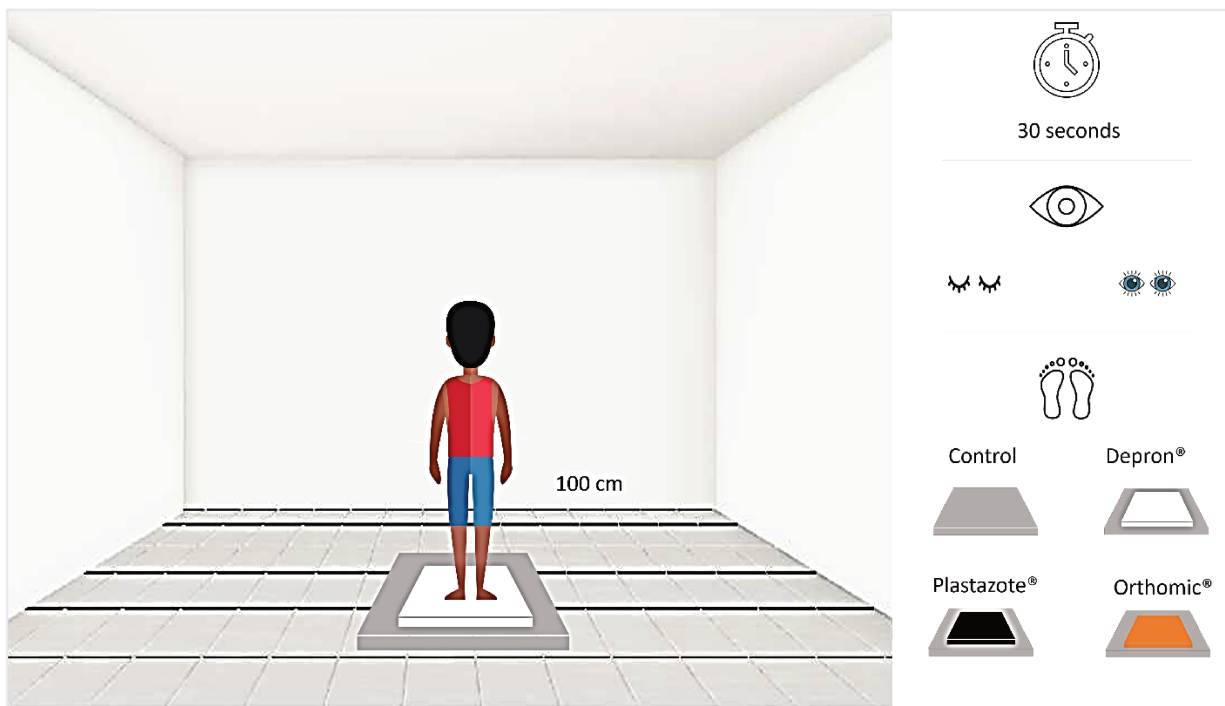


Figure 38: Illustration of the experimental standing balance task conditions (vision and foam)

B.3. Data analysis

- **Dependent Variables**

In order to determine if standing balance was affected by foam pad interposition, we first calculated the surface of CoP oscillations and the length of CoP displacement. We performed an initial analysis of the coefficients of variation for those parameters in order to choose the CoP variable showing the best between-trials reproducibility to compute the Plantar Quotient (PQ) and the Romberg Quotient (RQ). To this end, they were computed for each participant and each condition using the 3 repetition trials. These coefficients were in average 0.33 ± 0.18 for Surface

and 0.11 ± 0.01 for Length. The detailed values per conditions are illustrated on Figure 39. We then selected length to compute hereafter the PQ, as showing lower coefficient of variation than the ones computed using the surface ($p < 0.001$). As the task was to maintain posture as still as possible, whatever the conditions used, the best value recorded among the 3 trials was kept for the analysis.

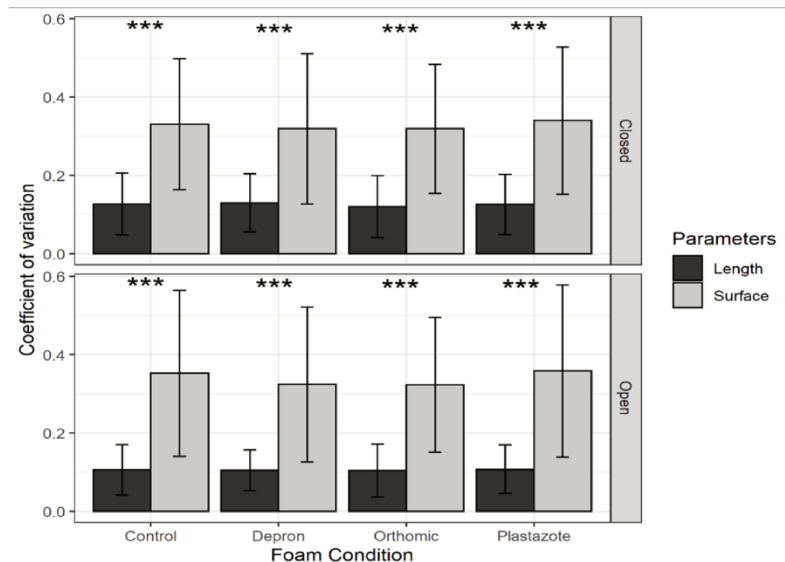


Figure 39: Coefficient of variation for Length of CoP displacement and Surface area of CoP regarding vision and foot conditions (Paired sample T tests were performed)

We computed the results of minimal Length, approximate Entropy on X and Y axis, Plantar Quotient and Romberg Quotient.

We computed PQ, as described in equation 3, using the variable length of CoP displacement since it was shown to have a good inter-trial reproducibility. PQ ratio can be calculated under different visual conditions for example, with eyes open or closed.

$$PQ = \frac{\text{Length of CoP displacement on foam}}{\text{Length of CoP displacement without foam}} \quad (3)$$

We computed RQ, as described in equation 4, using the same variable as in 3. RQ ratio can be calculated under different foot conditions (control, or foam pads).

$$RQ = \frac{\text{Length of CoP displacement eyes closed}}{\text{Length of CoP displacement eyes open}} \quad (4)$$

To further evaluate stability, we computed the approximate entropy on X axis and Y axis which is a measure to quantify the amount of regularity. Its value ranges between 0 (perfect regularity signal) and 1 (fully random signal).

- **Statistical analysis**

Statistics were performed using Jamovi® and R softwares. Level of significance was set to 0.05. Normality was assessed using the Shapiro-Wilk test.

For the following dependent variables: Length and Surface of CoP displacement, QR, QP, when the data were normally distributed, we performed a repeated measures Anova. When we had a non-normal distribution of the data, the non-parametric ART-Anova (aligned Rank Transformed) was used to evaluate main and interaction effects of foams and visual conditions on dependent variables. Pairwise comparisons were performed as post hoc analyses using Durbin-Conover tests.

For the sensitive evaluation test, when the data were normally distributed, a repeated Anova was performed. When we had a non-normal distribution of the data, a Friedman test was used to evaluate main effects between each aera. Pairwise comparisons were performed as post hoc analyses using Durbin-Conover tests.

B.4. Results

We analyzed the data of 131 participants out of the 132 recruited. Indeed, this participant showed an atypical behavior with a worse performance in the control condition (no foam and eyes opened). His results (on Length CoP displacement) being more than 3 standard deviations away from the average, we decided to remove this participant from the analysis.

- **Foot sensitive evaluation**

The descriptive statistics are in the table 4, computed for both feet:

Table 4: 2-point discrimination test results (mean and SD, IC_{95%}) for the 1st Metatarsal head zone (MH1), the 3rd and the 5th (MH3 and MH5), the big toe and the heel zone.

	MH1	MH3	MH5	Big Toe	Heel
Mean ± SD	10 ± 2.66	11.9± 3.07	10.9 ± 2.74	8.70 ± 2.19	11.7 ± 3.27
IC _{95%}	[9.7;10.3]	[11.5;12.3]	[10.6;11.2]	[8.44;8.97]	[11.3;12.1]

The Anova analysis highlighted a significative difference between all the aeras between them (except the 3rd metatarsal head and the Heel) with a better discrimination capacity for the big toe aera ($\chi^2=186$, $p<0.001$). Pairwise comparison is in the table below (Table 5).

Table 5: Pairwise comparisons between the foot aera on 2-point discrimination test (*: $p=0.05$, **: $p=0.01$, *** $p=0.001$)

	MH1	MH3	MH5	Big Toe	Heel
MH1		***	***	***	***
MH3			***	***	0,148
MH5				***	0,002
Big Toe					***

- **Descriptive statistic of CoP variables**

	Length		Approximate Entropy on X-axis		Approximate Entropy on Y-axis		PQ		RQ
	EO	EC	EO	EC	EO	EC	EO	EC	
Control									
Mean ± SD	235 ± 62	316 ± 91,1	0,159 ± 0,0570	0,186 ± 0,0592	0,153 ± 0,0723	0,2 ± 0,0855			1.35±0.223
Median ± IQR	221 [86,6]	313 [122]	0,154 [0,085]	0,174 [0,0746]	0,139 [0,099]	0,187 [0,132]			1.33[0.280]
IC _{95%}	[224 ;246]	[301 ;332]	[0.207;0.231]	[0.240;0.270]	[0.189;0.220]	[0.236;0.272]			[1.30;1.39]
Depron®									
Mean ± SD	238 ± 63,2	324 ± 103	0,163 ± 0,0547	0,190 ± 0,0709	0,158 ± 0,0663	0,201 ± 0,0805	1,02 ± 0,133	1,03 ± 0,138	1.36 ± 0.266
Median ± IQR	224 [75,3]	306 [135]	0,161 [0,0772]	0,177 [0,0951]	0,148 [0,0892]	0,188 [0,102]	1,01 [0,154]	1,01 [0,167]	1.35 [0.362]
IC _{95%}	[227 ;249]	[307 ;342]	[0.207;0.235]	[0.252; 0.285]	[0.202;0.233]	[0.243; 0.278]	[0.993 ;1.04]	[1.00 ;1.05]	[1.32;1.41]
Orthomic®									
Mean ± SD	237 ± 63,4	322 ± 93,6	0,159 ± 0,0580	0,183 ± 0,0677	0,154 ± 0,0737	0,2 ± 0,0796	1,01 ± 0,127	1,02 ± 0,132	1.37±0.265
Median ± IQR	223 [77,8]	305 [128]	0,149 [0,0765]	0,184 [0,107]	0,142 [0,0833]	0,192 [0,108]	1,01 [0,153]	0,01 [0,17]	1.33[0.3]
IC _{95%}	[226 ;248]	[306 ;338]	[0.206;0.234]	[0.235; 0.262]	[0.190;0.221]	[0.238;0.274]	[0.991 ;1.03]	[1.00 ;1.05]	[1.32;1.41]
Plastazote®									
Mean ± SD	236 ± 58,3	313 90,7	0,158 ± 0,054	0,186 ± 0,669	0,151 ± 0,0685	0,196 ± 0,0809	1,02 ± 0,138	1,00 ± 0,144	1.34±0.249
Median ± IQR	226 [72,2]	301 [124]	0,150 [0,074]	0,179 [0,102]	0,138 [0,096]	0,185 [0,114]	1,01 [0,161]	0,977 [0,016]	[1.32;0.306]
IC _{95%}	[226 ;246]	[298 ;329]	[0.218; 0.247]	[0.235; 0.265]	[0.205;0.239]	[0.238;0.274]	[0.985; 1.04]	[0.975; 1.02]	[1.29;1.38]

- **Effect of foam and visual conditions on Length of displacement, Surface and Approximative Entropy of CoP**

The ART-Anova did not highlighted any significant effect of foam on CoP displacement length, as well as entropy on X-axis and on Y-axis (Figure 40) (resp. $p=0.32$; $p=0.59$; $p=0.43$) nor interaction effect between foam and vision conditions (resp. $p=0.34$; $p=0.92$; $p=0.81$). Let us note that the associated effect size was very small (resp. 0.008, 0.001 and 0.002).

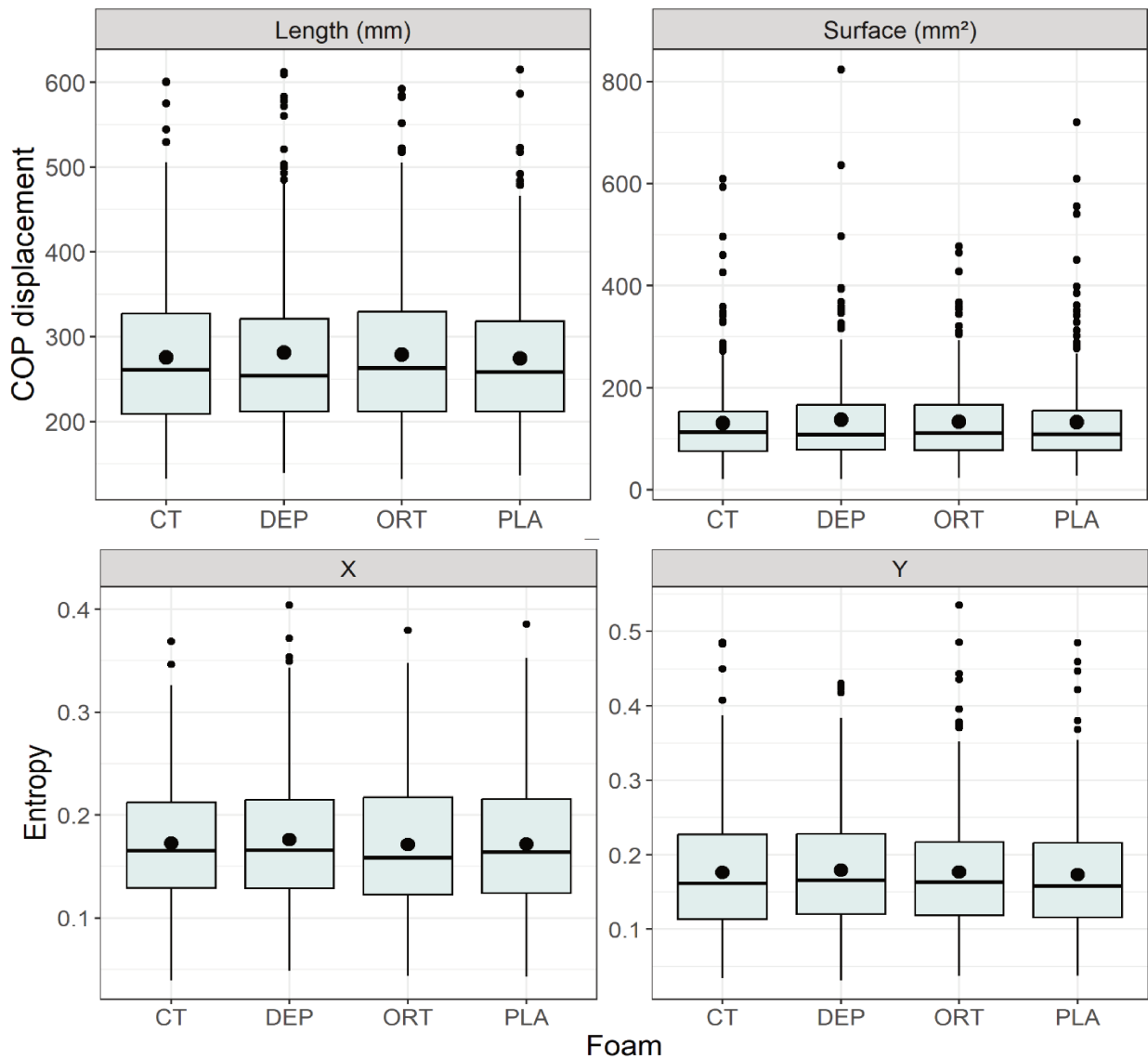


Figure 40: Length of displacement, Surface an approximative entropy on X and Y axis under 4-foot conditions: control (CT), Depron® (DEP), Orthomic® (ORT) and Plastazote® (PLA).

There was a significant effect of vision on CoP displacement length, as well as on entropy on X-axis and on Y-axis as shown on figure 41 (resp. $F(1,130) = 537.35$, $p < 2e-16$, $\eta^2_p = 0.80$; $F(1,130) = 51.98$, $p < 4.1e-11$, $\eta^2_p = 0.29$; $F(1,130) = 144.73$, $p < 2e-16$, $\eta^2_p = 0.53$). Post hoc analysis showed a significant difference between eyes closed and open with higher values when eyes were closed ($t(130) = 15.78$, $p < 0.0001$; $t(130) = 22.354$, $p < 0.0001$; $t(130) = 7.21$, $p < 0.0001$; $t(130) = 12.031$, $p < 0.0001$).

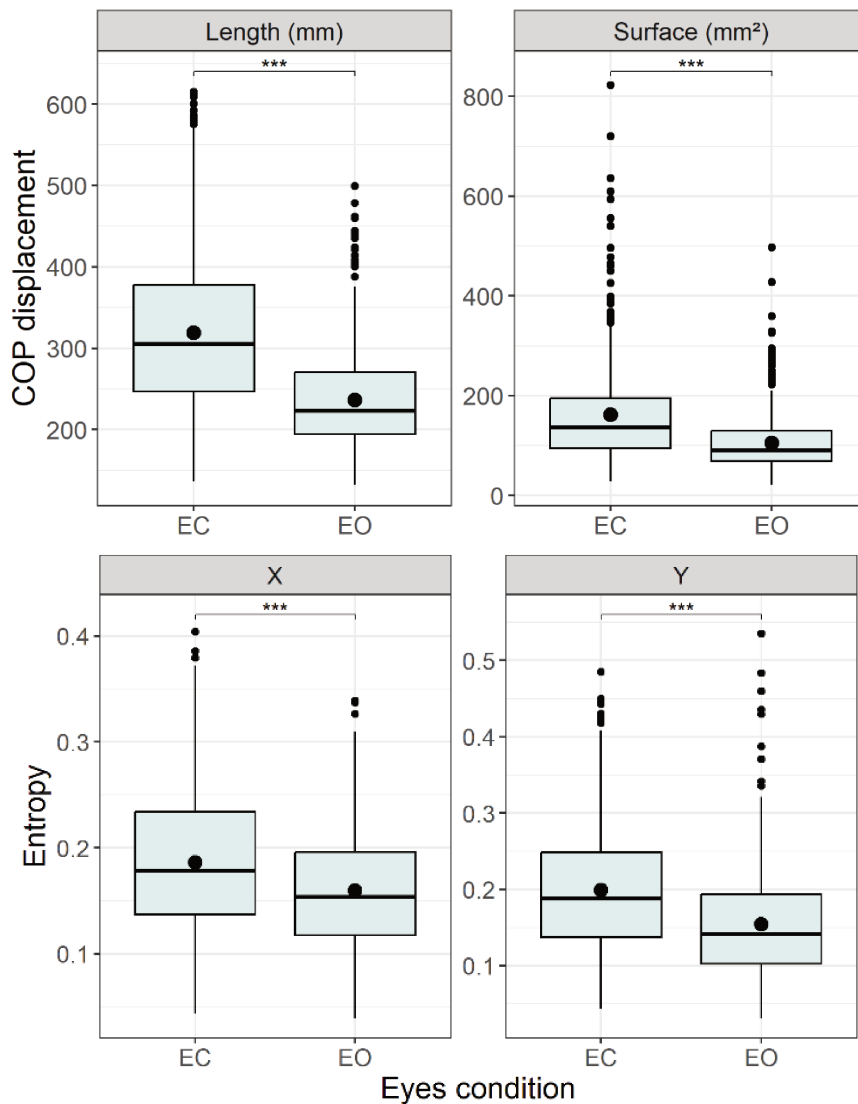


Figure 41: Length, Surface, Approximative entropy on X and Y axis under 2 visual conditions: eyes closed and open.

- **Effect of vision and foam on Plantar Quotient**

The ART-Anova highlighted a significant but very small effect of foam on Plantar quotient ($F(2,260) = 3.43, p < 0.03, \eta^2 p = 0.025$). Post hoc analysis showed a difference between Depron® and Plastazote® ($t(262) = 2.57, p = 0.02$) with Plastazote® making less perturbation on static stability than Depron®. No difference was highlighted between Depron® and Orthomic® ($p = 0.67$) and Orthomic® and Plastazote® ($p = 0.2$) (Figure 42).

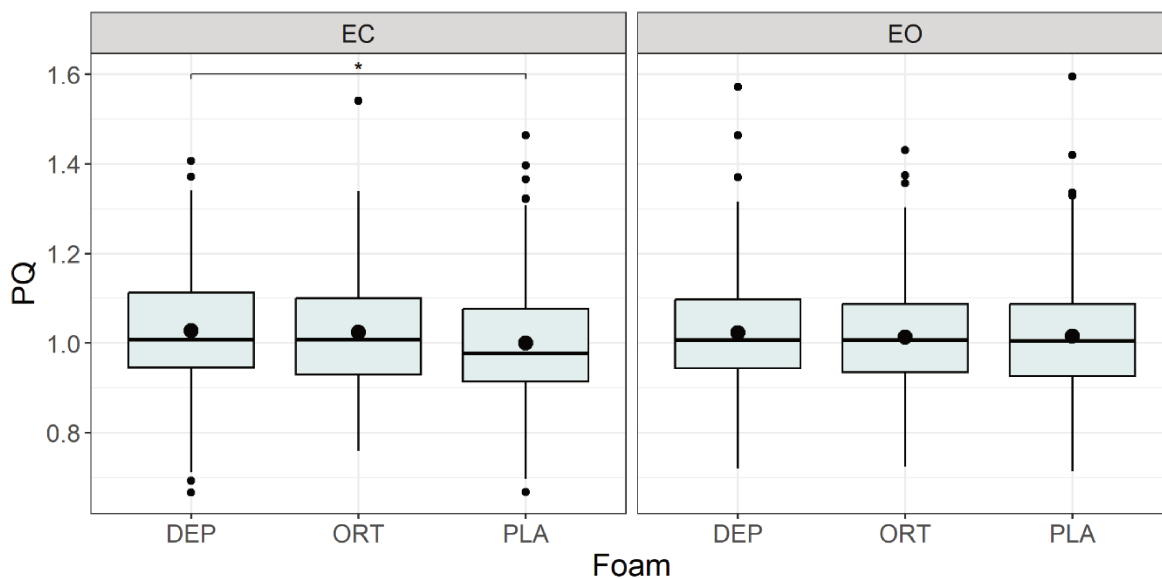


Figure 42: Plantar Quotient under 2 visual conditions (eyes closed and open) and 3 foams (Depron®, Orthomic® and Plastazote®)

- **Effect of vision and foam on Romberg Quotient**

The Friedman test highlighted no significant differences on the effect of foam on Romberg quotient (RQ) ($p = 0.462$) (Figure 43).

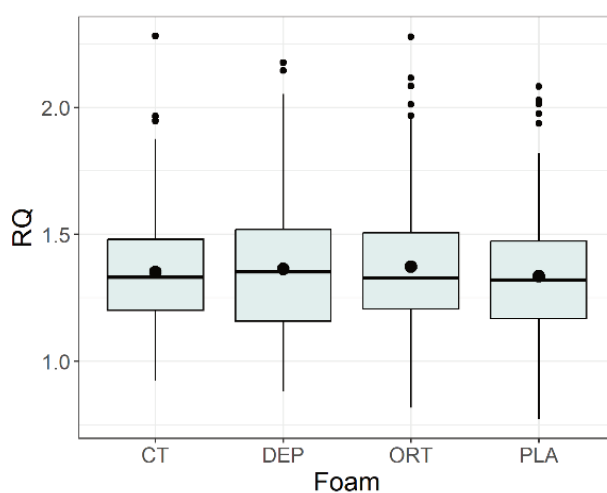


Figure 43: Romberg Quotient under 4 podal conditions: control, Depron®, Orthomic®, Plastazote®

C. Discussion

We were interested in evaluating the effect of a thin foam pad on postural control in healthy adults, in order to specify reference values for clinical applications. In addition, we would like to compare the effect of 2 clinically used and reusable foams with Depron®, initially employed to compute plantar quotient but which is not a reusable material.

First, the analysis of foot integration using the two-point discrimination test has yielded consistent results with the existing literature (Rinkel et al., 2017). It appears that sensitivity is more precise when assessing discrimination from the heel to the toes and from the middle to the lateral sides of the foot. The feet are similar to each other. Regarding Romberg quotient, which evaluates visual information role in standing balance, we observed an uprise of CoP parameters values (around 30%) which is the normal disturbance reaction, showing that our participants did not suffer from any visual information integration problem.

Interposition of a thin foam pad did not challenge our participants. Indeed, the PQ are of the same order for Depron®, Orthomic® and Plastazote® (respectively: 1.02, 1.03, 1.00) as well as their standard deviation (respectively: 0.137, 0.132, 0.144). It is bounded by [0.32;1.57] for open eyes and [0.66 ;1.41] in closed eyes situations. In the protocol used conditions, foam doesn't disturb postural control whereas eyes open or closed. A physiological response in those conditions is no differences in CoP parameters. Regarding Romberg quotient, which evaluate visual information role in static stability, we observed an uprise of CoP parameters values (around 30%) which is the normal disturbance reaction (Alexander & Kinney LaPier, 1998), showing that our participants did not suffer from any visual information integration problem.

First, results showed that the 3 foams used in this study induced a minimal disturbance on postural control. Indeed, when considering length as well as approximate entropy of CoP displacement during a 30s standing task, results did not show any effect of foam. In addition, when considering the Plantar Quotient (PQ, i.e., the ratio between COP variable with and without foam) for CoP path length, the computed values were respectively 1,02 for Depron® and 1,01 for Orthomic® and Plastazote® (with eyes open). Effect size of foam condition was 0.026. Even if post hoc analysis showed a significant difference between Depron® and Plastazote®, the foam impact appears to be marginal. However, as Depron® and Orthomic® have closer results on indentation test than Plastazote®, foam viscoelasticity characteristic seems to create a minimal impact on static balance and should be informed in studies.

These results are not in line with the literature which has demonstrated that foam is a consistent perturbation on postural stability (Abrahamová & Hlavačka, 2008; Bressel et al., 2007; Fujimoto et al., 2012; Hammami et al., 2014). However, as discussed in the introduction part, the foam characteristics are not uniformized. Foam thickness varies between protocols. In our study, we used a thin foam to limit the use of lower limb muscles and then evaluate the perturbation of the plantar mechanoreceptors. While our results were not able to show an effect of the foam on postural control, they might suggest that there could be a minimal thickness to destabilize posture.

In addition, our results are not in adequacy with previous works using Depron® foam showing an effect of foam on PQ, which was equal to 1.12 ± 0.39 (considering mean surface parameter) (Foisly & Kapoula, 2017). If we consider the mean surface parameter, we obtain 1.11 ± 0.62 eyes open

and 1.17 ± 0.9 eyes closed which is closed to previous work but the $IC_{95\%}$ for this parameter is respectively $[1.02;1.33]$ eyes closed and $[1.01;1.22]$ eyes open. Our distributions are however not the same. We obtain a Gaussian type of distribution with no evident sub population highlighted (Figure 44). To better understand those differences, we proposed an additional analysis similar to this study. We then divided our population into two groups based on PQ results: <1 or >1 , as it was done this article. To this end, we relied on the average values of Surface and CoP displacement length measured during the 3 repetitions to compute PQ variables. We also considered the minimum value of length of CoP displacement to compare with our own analysis.

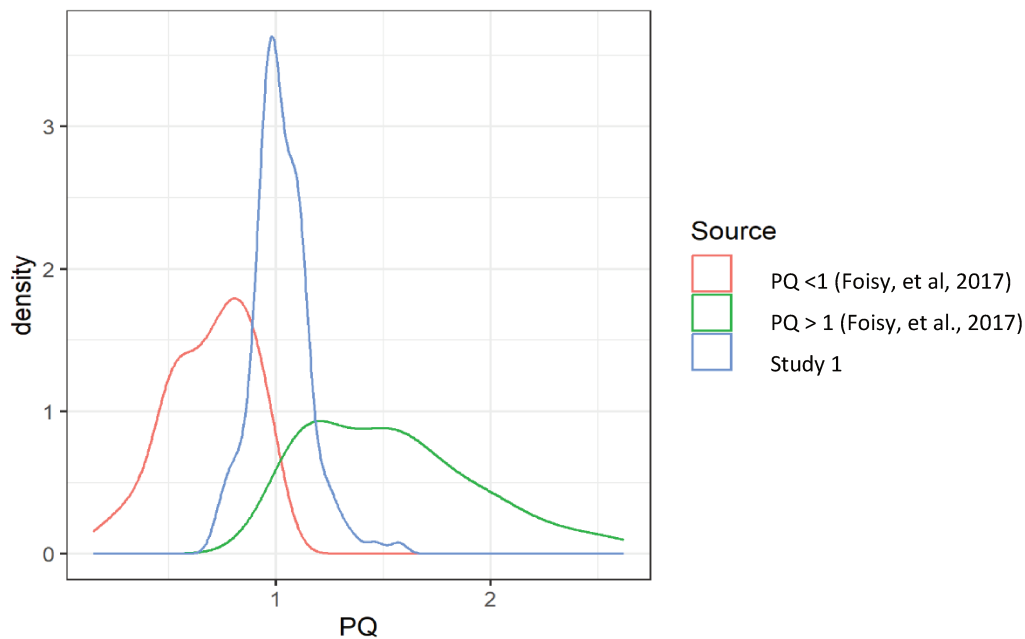


Figure 44: PQ density obtain on Study 1 data and generate data from Foisy (2017).

First, the repartition of participants is different regarding the CoP parameters considered: Average surface showed the following distribution of participants: $PQ<1=64$ and $PQ>1=67$. In comparison, PQ computed with CoP displacement length, distributions of participants within those two groups, are respectively 63 and 68 for minimal length, and 58 and 73 for average length. Moreover, if we consider individual participants and their distribution within each group of PQ (<1 group or >1), 35.9% are not belonging to the same group if we compare average surface vs. minimal length, 32.1% if we compare average length vs. average surface and 32.8% if we compare average length vs. minimal length. Therefore, if patients are categorized by their PQ, it is fundamental to rely on the same variables for its computation. As in clinical practice, 3 repetitions are not often performed due to time constraints, considering the Minimum Length of CoP displacement seems to be a more realistic choice as we gave the instruction of standing as still as possible.

If we take a closer look at the PQ distribution in the previous study, the results are more similar to a distribution observed at a 2-meter distance from the wall. However, it's worth noting that the previous study considered PQ results in a 40 cm distance from the wall condition. Another factor that might explain the differences with the previous work is the characteristics of the available

visual information. In our study, we provided a neutral visual environment, with participants standing 1 meter away from a white wall with no additional visual cues.

In contrast Foisy et al. paper based its visual conditions on the distance from the wall (40 cm or 200 cm) and the presence or absence of a visual target. It is important to note that visual convergence is linked to better postural stability, while a textured visual field is associated with more challenging stability. Therefore, the visual characteristics of the experimental environment play a crucial role.

The lack of visual information in our protocol might have reduced the impact of the foam on static stability, suggesting that the recorded imbalance could be due to a deficit in integrating visual information. However, visual information can take various forms and is not standardized across studies. Therefore, it's essential to carefully report these conditions in future studies to standardize procedures and facilitate result comparisons.

To conclude, our results showed that Orthomic® is an ecological replacement to Depron®. By considering its norms, CoP displacement length and are respectively 238 ± 63.2 and 237 ± 63.4 with open eyes and a 1 meter away from a white wall. But technical information of foam characteristics is needed such as foam lifetime regarding mass loaded, repetition of use.

Future work is then needed to better understand the difference between our results and previous work and will be the subject of the next two studies in this chapter. As the visual information is the main difference between the 2 studies, evaluating its impact (visual field, convergence) on stability with foam pad could highlight if one visual condition is more in conflict with foot information. This implies to consider the distance to the wall as well as the type of visual target.

Another future work could be to compare results on plantar quotient and foot orthoses information integration. The Plantar Quotient distribution on Depron® is continuous and bounded between [0.32;1.57] for open eyes in our study. Future work could be to observe different subpopulations of this cohort. Considering that a normal response is a PQ around 1.02 ± 0.136 with 95% confidence interval [0.993 ;1.04], comparing a physiological subpopulation to the extreme subpopulations (minimum PQ and maximum PQ) on orthopedic insoles could explain if the PQ is a useful indicator about podal integration.

Study 2: Visual cues and Plantar Quotient

A. Introduction

Visual information primarily transmitted through the primary visual pathway is crucial for maintaining balance. Other visual parameters impact posture as well. The distance to the target during a static position influences stability. Stability is improved when the target is at 40 cm compared to 200 cm (Kapoula & Lê, 2006). The use of high-frequency visual information and ocular convergence also enhances postural control. Furthermore, a loss of visual motion perception leads to postural instability. Loss of peripheral visual field perception also results in reduced stability except in the anterior-posterior direction (Taneda et al., 2021). Visual flow allows an individual to perceive environmental motion and plays a crucial role in postural stabilization (Raffi et al., 2014). Variation in visual flow modifies postural responses. For example, changes in the depth of a fixed target modulate postural instability (Kapoula & Lê, 2006). The perception of target mobility also increases instability (Gautier et al., 2008). All these findings emphasize the importance of visual information intake during a static task.

Visual targets modify postural responses. When fixing one of four targets with varying depth effects, subjects exhibit more instability as the depth of the target increases. The visual system plays a major role in postural control and maintenance (Patel et al., 2011). However few studies provides details on the targets used (size, shape, patterns) (Fransson et al., 2007; Patel et al., 2008).

Visual flow is also a parameter to consider when analyzing the visual input's impact on static balance. Self-Movements while standing generate an optical flow that regulates posture (Gibson, 2014; Neisser, 1994). The optical flow field carries information about the movement of external objects relative to the observer and the observer's movements relative to a stable environment.

The interposition of foam appears to increase postural oscillations (Boonsinsukh et al., 2020; Foisy & Kapoula, 2017; Peterka, 2018). Some studies have examined the interaction of these two systems but with different visual or plantar experimental conditions. All of these challenge balance with an increase in postural oscillations. However, variations in foam, in terms of thickness or height, as well as variations in visual information, make it difficult to compare between studies. In practice, many different foams with different characteristics can be used, along with different clinical setups (wall, visual environment). If obtained responses are "foam-dependent" and "vision-dependent," the results are challenging to extrapolate and predict. Some studies have examined their interaction with different visual experimental conditions. The work of Foisy et al. (2017) shows that a subset of their participants exhibits podal inefficiency: better stability on the foam Depron® (6 mm) than on a hard floor with a 40 cm away target, but not with a 200 cm one. Our previous work did not highlight any effect of Depron® on stability. As we did not provide any visual target, does the effects observed in the studies, while participants are on foam, linked to a podal information capacity or a visual one?

The objective of this study is to better understand the impact of the visual environment on the static balance of healthy adults, particularly the distance to the wall and the type of presented

target. We aimed at extending the study by Foisy and colleagues (Foisy & Kapoula, 2017) to different visual information's. Our hypotheses are that as the distance to the wall increases, static control is more disrupted. A textured target, which increase visual flow, would therefore allow for greater stabilization compared to other conditions. A second objective is to evaluate a potential visuo-podal interaction caused by the interposition of a foam pad and the visual conditions presented. Our hypothesis is that the interposition of a foam pad, coupled with challenged changes in the visual environment, induce increased imbalance on healthy adults.

B. Material and method

B.1. Participants

76 healthy adult participants (52 men, 24 women) volunteered for this study and gave their informed consent. They were 22.6 ± 3.77 y. o, 170 ± 9.66 cm tall and weighed 62.7 ± 10.8 kg. As we aimed at compared our results to previous study, the sample size calculation was based on them ($d = 0.77$) (Foisy & Kapoula, 2017). Participants should not have any balance disorders (inner ear, vision) and be taking any medication that can disturb balance. They must not have undergone a recent trauma of the lower limbs (less than 3 months or in the course of rehabilitation). Pregnant women and people above 45 years old were not included. Conditions like presbyopia are age-related and limiting them to 45 years old helps prevent non-inclusion ahead of time. To ensure homogeneity in the visual abilities of the participants, orthoptic tests were conducted.

To be included in the study, the participant must meet the following visual criteria:

- Ocular motility should not exhibit limitations in version or duction.
- Convergence reflex should be triggered.
- The near point of convergence should be equal to or less than 7 cm.
- Stereoscopic vision should be equal to or less than 120 arc seconds.
- The near point of accommodation should be equal to or less than the theoretical norm for age.
- Binocular accommodation amplitudes should be a minimum of 10 cycles per minute.
- Distance visual acuity should be greater than or equal to 10/10.
- Near visual acuity should be less than or equal to P2.
- Ocular deviation should not exhibit tropia. Exophorias-tropias are accepted under the condition of having Stereoscopic vision within expected norms and no functional signs.

These criteria were selected based on the literature (Agathos et al., 2015; Foisy & Kapoula, 2016) and the input of professional optometrist(Service ophthalmologie CHU Rennes³)

If needed, their visual correction was worn. Depending on the results, the participant will be advised to consult an ophthalmologist or orthoptist for a more in-depth evaluation.

We excluded 47% of volunteers in order to have 76 visual physiological participants.

³ Ophthalmology Department of the University Hospital Center in Rennes, France

B.2. Experimental design

• **Stabilometry platform**

In order to measure CoP position over time, we used the stabilometry platform Fusyo (Medicaptureur® (France)). It has a wedge to normalize the position of the feet, with an opening angle of 30°. The platform was placed in front of a white wall 40 or 200 cm away from the eyes position. Different visual conditions were assessed (eyes closed, no target, dot and dot included in a texture image).

• **Targets and distance to the wall**

Our study aims at comparing postural control considering visual information. Two distances from the wall were selected based on previous study (40 cm and 200 cm away) (Foisy & Kapoula, 2017; Kapoula & Lê, 2006).

4 visual information were tested:

- no information with eyes closed,
- normal information with a white wall in front of participants,
- simple red dot in front of participants,
- red dot in the middle of a textured image.

The size of the dot and the image were chosen based on literature (Fransson et al., 2007; Kapoula & Lê, 2006; Patel et al., 2008) (at 40 cm, the diameter of the target was 0.5 cm, and the size of the image was 4x6 cm; at 200 cm, it was respectively 2.5 cm diameter and 20x30 cm).

• **Foam Pad**

As we want to compare this study to the literature and to our previous results, we chose Depron® (6mm thick).

• **Environmental conditions**

This experimentation was carried out within the IFPEK's care clinic in Rennes, France (training institute for podiatry, occupational therapy and physiotherapy).

We used a repeated measure design. Participants were asked to stand still during 30s on a stabilometry platform in a given posture (feet 30° open, looking straight forward, arms along the body, without speaking) (Figure 45). We considered the following factors:

- Foam (2): control condition (no foam), Depron®. Foams were located on the stabilometry platform.
- Vision (4): eyes closed or open, simple dot and a dot inside an image. Visual cues were located in front of participants 'eyes.
- Distance to the wall (2): 40 cm or 200 cm away from a wall.

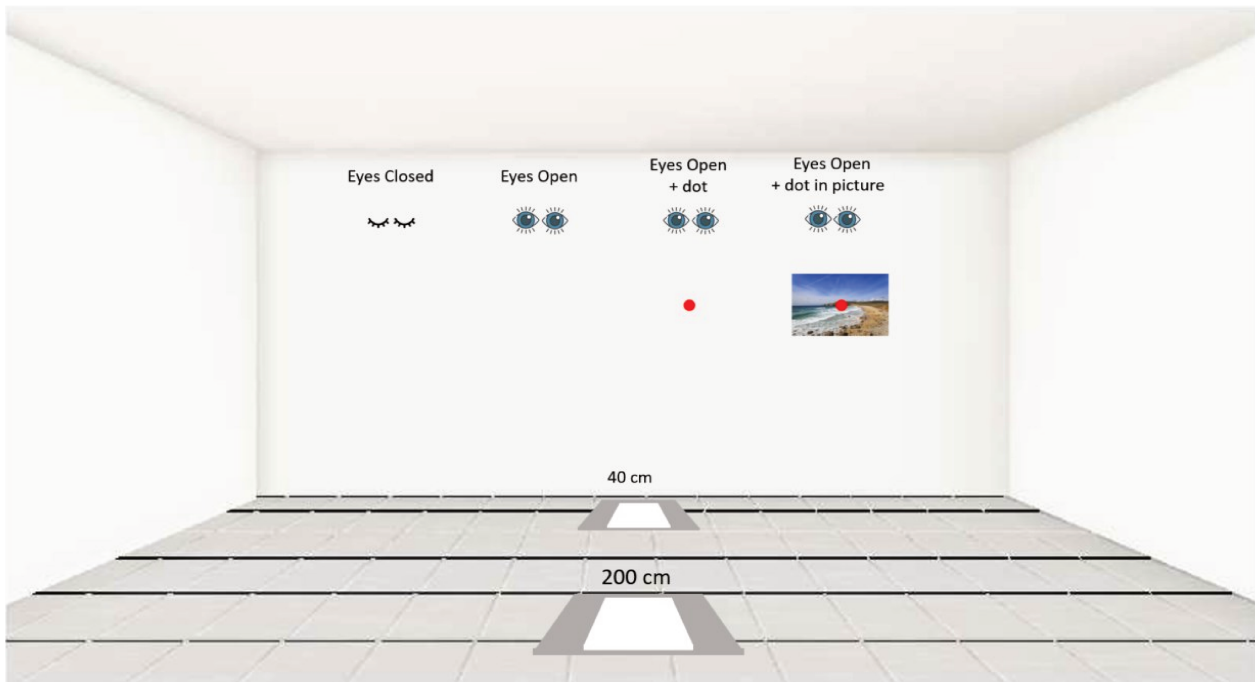


Figure 45: Illustration of the experimental environment as well as the experimental conditions, namely 2 distances from the wall (40 and 200 cm) and 4 visual conditions (eyes closed, eyes open, eyes open with a red dot and eyes open with a red dot within a

A condition corresponded to a combination of the different levels of the foam and vision factor. Three trials were performed for each condition. Between each trial, a rest time of at least 30s was imposed. In total participants performed 54 trials in a randomized order:

- 3 repetitions * 4 visions * 2 foams * 2 distances (Figure 46 (A et B))
- 3 repetitions * 2 distances from the wall (200 and 40 cm) * 1 vision (dot at 40 cm) (Figure 46 (C)).

A session lasted 60 minutes. Foams were changed between each trial.

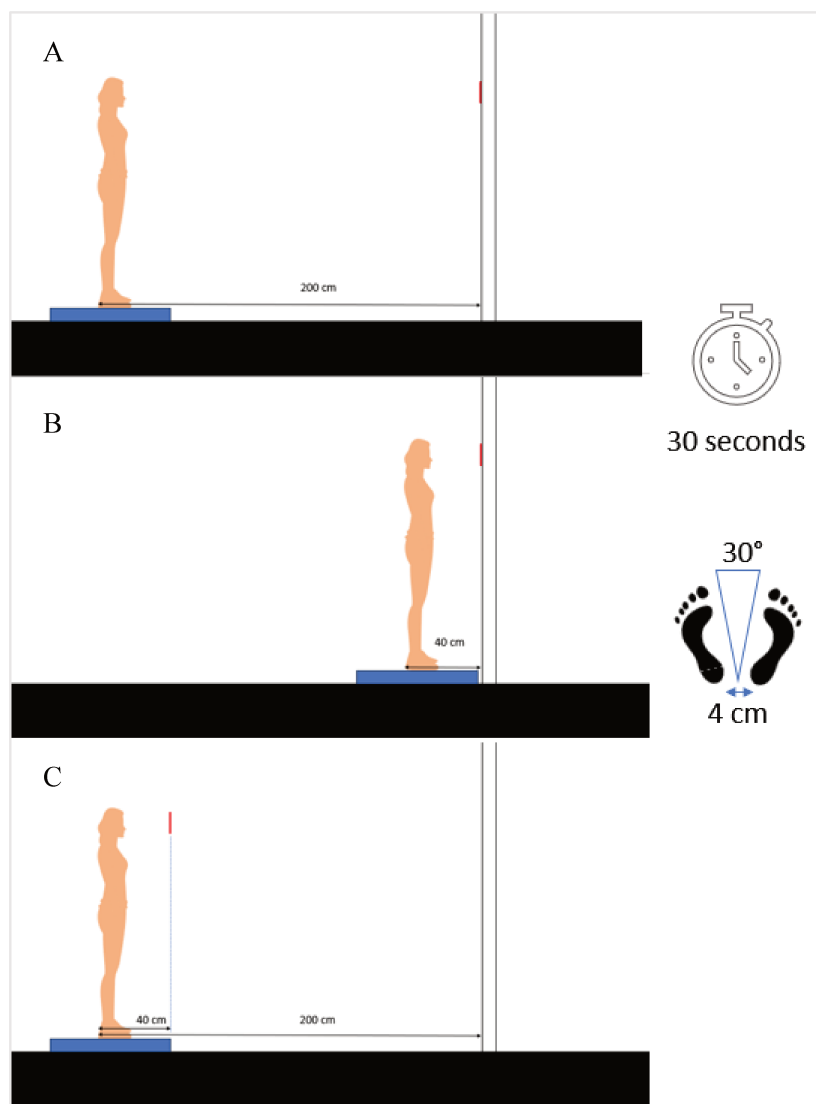


Figure 46: Study 2 environmental conditions
 A: Wall and targets at 200 cm from the participant
 B: wall and target at 40 cm from the participant
 C: Wall at 200 cm but target at 40 cm from the participant

B.3. Data analysis

- **Dependent variables**

In order to determine if standing balance was affected by visual information and foam pad interposition, we first calculated the surface of CoP oscillations and the length of CoP displacement. We performed an initial analysis of the coefficients of variation for those parameters in order to choose the CoP variable showing the best between-trials reproducibility to compute the Plantar Quotient (PQ) and the Romberg Quotient (RQ). To this end, there were computed for each participant and each condition using the 3 repetition trials. These coefficients were in average 0.30 ± 0.16 for Surface and 0.11 ± 0.06 for Length. We then selected length (as in Study 1 as the

variability of CoP parameters was similar) to compute hereafter the PQ and the RQ, as showing lower coefficient of variation than the ones computed using the surface ($p < 0.001$).

We computed PQ and RQ, as described in equations 3 (p.73) and 5, using the variable length of CoP displacement since it was shown to have a good inter-trial reproducibility. PQ ratio can be calculated under different visual conditions. RQ ratio can be calculated under different foot conditions and for the different visual condition tested.

$$PQ = \frac{\text{Length of CoP displacement on foam}}{\text{Length of CoP displacement without foam}} \quad (3)$$

$$RQ = \frac{\text{Length of CoP displacement eyes closed}}{\text{Length of CoP displacement eyes open (no target / dot / dot within an image)}} \quad (5)$$

As the task was to maintain posture as still as possible, whatever the conditions used, the best value recorded among the 3 trials was kept for the analysis.

- **Statistical analysis**

Statistics were performed using Jamovi® and R softwares. Level of significance was set to 0.05. Normality was assessed using the Shapiro-Wilk test. When the data were normally distributed, we performed a repeated measures Anova. When we had a non-normal distribution of the data, the non-parametric ART-Anova (aligned Rank Transformed) was used to evaluate main and interaction effects of foams and visual conditions on dependent variables. Pairwise comparisons were performed as post hoc analyses using Durbin-Conover tests.

B.4. Results

- **Effect of foam and vision on CoP Length of displacement and surface area**

Descriptive statistics

Tables 6 and 7 compute mean \pm Standard deviation, median \pm Interquartile Range and Confidence interval at 95% for Surface and Length of displacement of CoP under 2 podal conditions (control and Depron), 4 visual conditions (EC, EO, Dot and Dot + image) and 2 distances to the wall conditions (40 and 200 cm).

Table 6: Surface of COP displacement descriptives statistics (Mean, Standard deviation, Median, IQR, IC_{95%}) for the 4 visual conditions and 2-foot conditions.

Surface (mm ²)								
Control		Depron®		Control		Depron®		
EO	EC	EO	EC	Dot	Dot + image	Dot	Dot + image	
40 cm								
Mean ± SD	106 ± 59,6	196 ± 136	105 ± 63,4	209 ± 136	101 ± 82	108 ± 67,6	113 ± 80	93,9 ± 51
Median ± IQR	97,7 [72,5]	156 [132]	94,2 [63,4]	182 [136]	76,8 [58,6]	92,3 [79]	89,5 [81,9]	86,1 [57,4]
IC _{95%}	[92,2 ;119]	[165 ;227]	[90,6;0.120]	[178;0.240]	[82,4 ;120]	[93 ;124]	[94,7 ;131]	[82,3;106]
200 cm								
Mean ± SD	194 ± 124	214 ± 124	192 ± 110	201 ± 124	186 ± 107	175 ± 116	183 ± 113	171 ± 104
Median ± IQR	159 [157]	177 [174]	168 [129]	172 [152]	157 [126]	137 [148]	148 [122]	142[120]
IC _{95%}	[166 ;223]	[185 ;242]	[167;217]	[173; 230]	[162 ;211]	[148 ;201]	[157;209]	[147; 194]

Table 7:: Length of COP displacement descriptives statistics (Mean, Standard deviation, Median, IQR, IC_{95%}) for the 4 visual conditions and 2-foot conditions.

Length of CoP displacement(mm)								
Control		Depron®		Control		Depron®		
EO	EC	EO	EC	Dot	Dot + image	Dot	Dot + image	
40 cm								
Mean ± SD	252 ± 73,6	348 ± 107	252 ± 74,6	367 ± 115	250 ± 78,2	349 ± 70	258 ± 85,1	239 ± 57,7
Median ± IQR	238 [82,9]	328 [126]	241 [81,6]	353 [123]	238 [68,3]	239 [81,8]	237 [87,7]	226 [69]
IC _{95%}	[235 ;269]	[324 ;372]	[235;269]	[340;393]	[232 ;267]	[233 ;265]	[239;277]	[226;252]
200 cm								
Mean ± SD	300 ± 80,4	368 ± 111	313 ± 82,1	361 ± 112	302 ± 78,3	289 ± 75,6	304 ± 77,8	289 ± 112
Median ± IQR	284 [100]	346 [142]	303 [107]	339 [128]	304 [108]	281 [87,6]	293 [101]	284 [112]
IC _{95%}	[282 ;319]	[342 ;393]	[294;332]	[336;387]	[284 ;320]	[272 ;306]	[286; 322]	[273; 305]

Distance to the wall

There was a significant effect of the distance to the wall on CoP displacement length and Surface as shown on figure 47 (resp. $F(1,75)=87,37$, $p<2e-14$, $\eta^2p=0.53$ and $F(1,75)=107.47$, $p<2e-16$, $\eta^2p=0.59$). Post hoc analysis showed a significant difference between a distance of 40 cm and 200 cm to the wall with higher values when the wall is at 200 cm ($t(130)=22.354$, $p<0.0001$; $t(130)=-10.38$, $p<0.0001$).

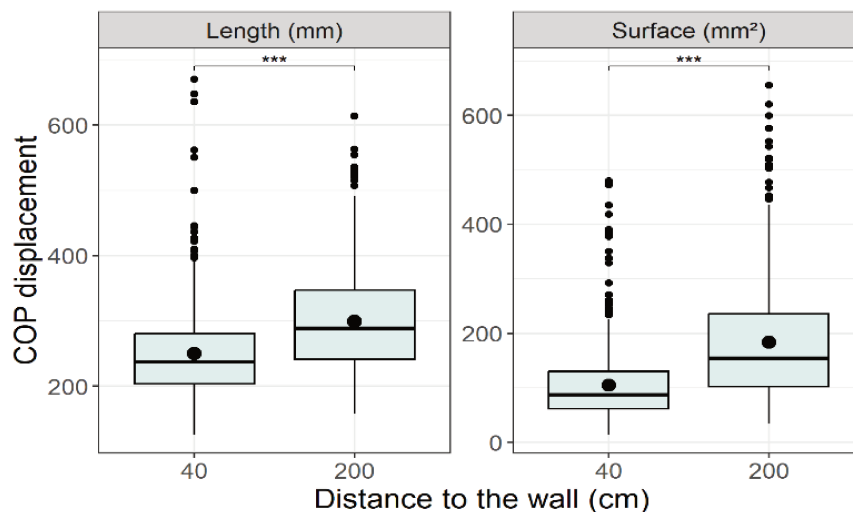


Figure 47: Length and Surface of CoP displacement under 2 wall distances: 40 and 200 cm.

To better understand the impact of a 40 cm away wall we analyzed 2 situations (with and without Depron®):

- Distance to the wall: 40 cm – Visual target: Dot at 40 cm
- Distance to the wall: 200 cm – Visual target: Dot at 40 cm

A situation

and:

- Distance to the wall: 40 cm – Visual target: eyes closed
- Distance to the wall: 200 cm – Visual target: eyes closed

B situation

There was a significant effect of the distance to the wall on Length of displacement and Surface of CoP in the A situation with no foam as shown on figure 48 (resp. $\chi^2(1)=11.8$, $p<0.001$ and $\chi^2(1)=17.1$, $p<0.001$). With Depron® under feet compare to control condition, the Friedman test did not highlight any significant difference (resp. $p=0.25$ and $p=0.36$).

There was a significant effect of the distance to the wall on Surface of CoP in the B situation as shown on figure 48 ($\chi^2(1)=7.58$, $p<0.006$). With Depron® under feet, the Friedman test did not highlight any significant difference (resp. $p=0.108$). Let us notice that we did not highlight a significant difference on Length of displacement of CoP eyes closed between no foam and Depron® (resp. $p=0.07$ and $p=0.65$).

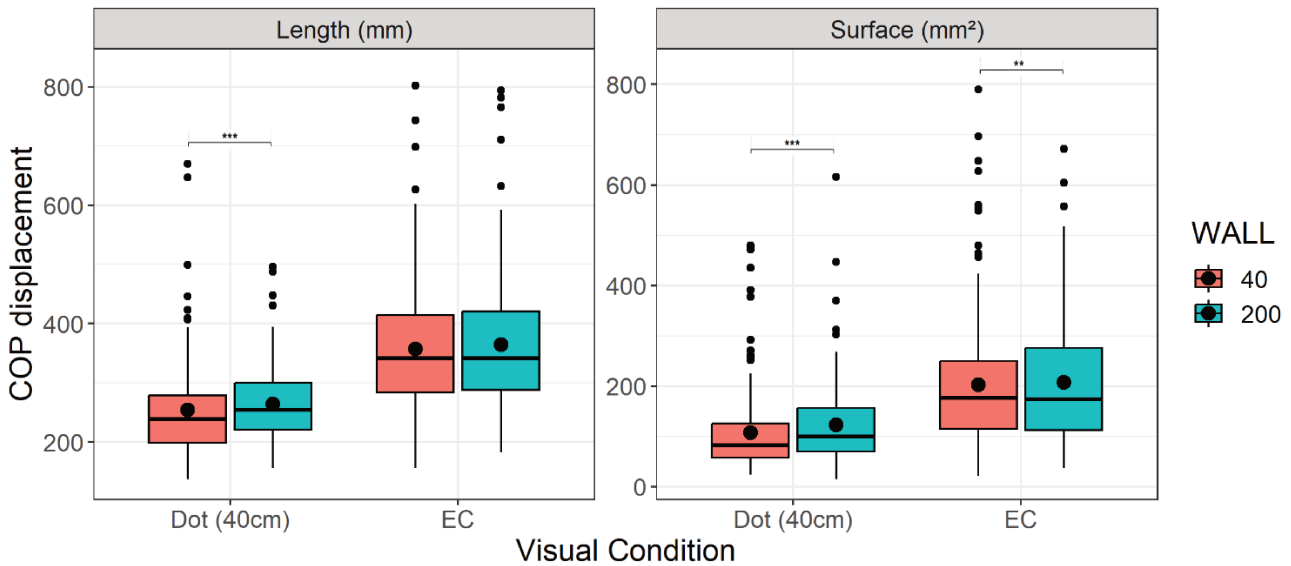


Figure 48: Length and surface of CoP displacement, with a dot or eyes closed as visual factor, under 2 distances from the wall (40 and 200 cm).

Vision

We first analyzed the eyes **closed conditions**, and **all the eyes open conditions**.

There was a significant effect of vision on CoP displacement Length and Surface as shown on figure 49 (resp. $F(3,225) = 192.25$, $p < 2e-16$, $\eta^2 p = 0.72$ and $F(3,225) = 71.7$, $p < 2e-16$, $\eta^2 p = 0.49$). Post hoc analysis showed a significant difference between eyes closed and eyes open with no target, eyes open and a dot and eyes open with a dot within an image with higher values when the eyes were closed (resp. $t(225) = -18.095$, $p < 0.0001$; $t(225) = -18.70$, $p < 0.0001$; $t(225) = -21.40$, $p < 0.0001$ for the length, $t(225) = 10$, $p < 0.0001$; $t(225) = -11.63$, $p < 0.0001$; $t(225) = -13.35$, $p < 0.0001$ for the Surface).

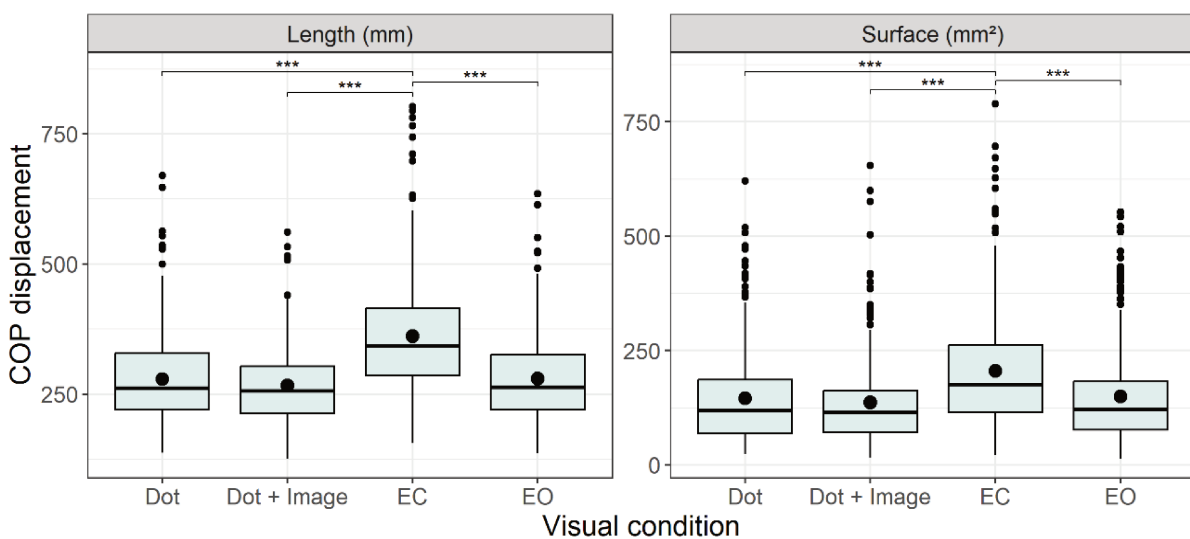


Figure 49: Length and Surface of CoP displacement under 4 visual conditions (eyes closed, open, with a dot and with a dot within an image)

If we compare **the eyes open conditions** only (no target, dot and dot within a texture image):

There was a significant effect of vision on CoP displacement length and Surface as shown on figure 50 (resp. $F(2,150) = 8.84$, $p < 2e-4$, $\eta^2 p = 0.11$ and $F(2,150) = 6.83$, $p < 0.0015$, $\eta^2 p = 0.08$). Let us note that the associated effect size for Surface was very small (0.08).

Post hoc analysis showed a significant difference between the condition “dot + image” and the conditions “EO” or “dot” with smaller values with the texture image for length ($t(150) = 3.94$, $p < 0.0004$; $t(150) = 3.24$, $p < 0.004$), and between “dot + image” and “EO” for Surface ($t(150) = 3.70$, $p < 0.0009$).

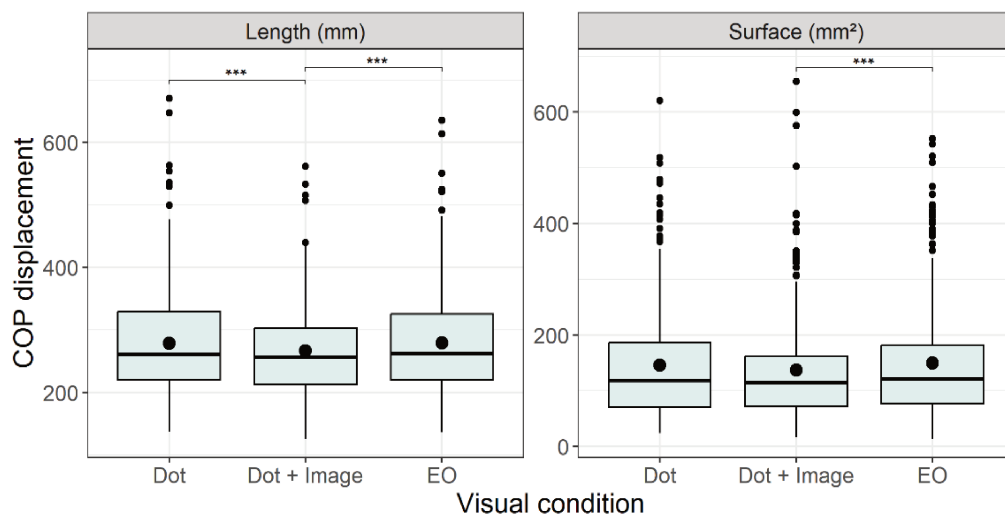


Figure 50: Length and surface of CoP displacement eyes open with 3 different visual information (control, dot and dot within an image)

Foam

The ART-Anova did not highlighted any significant effect of foam on CoP displacement length, as well as Surface (resp. $p = 0.22$; $p = 0.9$) nor interaction effect between foam and wall distance or visual conditions (resp. $p = 0.17$ and $p = 0.07$ for length, $p = 0.70$; $p = 0.30$ for Surface).

- **Effect of foam and vision on Plantar Quotient**

Descriptive statistics were computed into table 8.

Table 8: Mean \pm SD, Median \pm IQR and IC_{95%} for PQ under 4 visual conditions (EC, EO, Dot and Dot + image)

Plantar Quotient				
	PQ		PQ _{Dot}	PQ _{Dot + image}
	EO	EC	EO	EO
40 cm				
Mean \pm SD	1,01 \pm 0,129	1,06 \pm 0,148	1,04 \pm 0,141	0,973 \pm 0,126
Median \pm IQR	0,992 [0,164]	1,05 [0,195]	1,02 [0,155]	0,978 [0,147]
IC _{95%}	[0,98 ;1,04]	[1,03 ;1,09]	[1,00;1,07]	[0,944;1]
200 cm				
Mean \pm SD	1,05 \pm 0,140	0,991 \pm 0,126	1,01 \pm 0,125	1,01 \pm 0,139
Median \pm IQR	1,04 [0,197]	0,981 [0,157]	1,00 [0,136]	1,01 [0,190]
IC _{95%}	[1,02 ;1,08]	[0,962 ;1,02]	[0,986;1,04]	[0,982;1,05]

We first analyzed **all the visual conditions** together (Eyes closed and all the eyes open ones).

The ART-Anova did not highlighted any significant effect of wall distance or visual condition on Plantar Quotient (resp. $p=0.76$; $p=0.06$) but a small interaction effect between visual conditions and wall distance conditions ($F(3.225) = 5.86$, $p < 0.0007$, $\eta^2 p = 0.007$) (Figure 51).

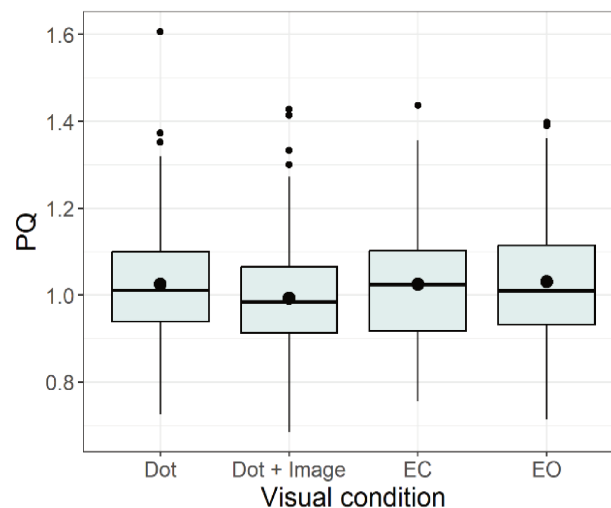


Figure 51: Plantar Quotient under 4 visual conditions (eyes closed, open, with a dot and with a dot within an image)

We analyzed the **open eyes conditions** (eyes open, dot and dot + image).

There was a significant effect of visual condition on PQ as shown on figure 52 (resp. $F(2,150) = 3.43$, $p = 0.035$, $\eta^2 p = 0.04$) with significant different values between “dot + image” and EO with lower PQ score for “Dot + Image”.

Post hoc analysis showed a significant difference between the condition “dot + image” and the conditions “no target” with smaller values with the “no target” condition for PQ ($t(150) = 2.45$, $p < 0.04$).

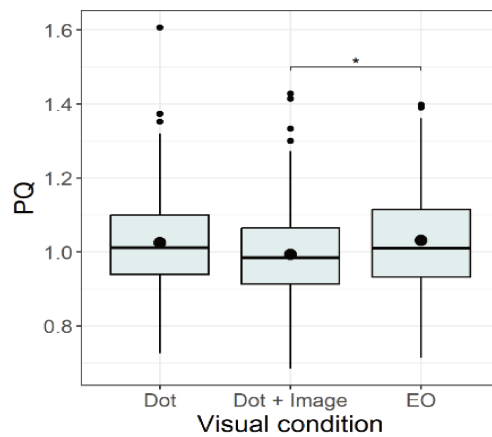


Figure 52: Plantar quotient under the 3 visual conditions (control, dot and dot + image)

We computed PQ with the A situation:

- Distance to the wall: 40 cm – Visual target: Dot at 40 cm
- Distance to the wall: 200 cm – Visual target: Dot at 40 cm

A situation

There was a significant effect of the distance to the wall (40 cm and 200 cm) on Plantar Quotient for situation A and B as shown on figure 53 (resp. $\chi^2(1) = 10.3$, $p = 0.001$).

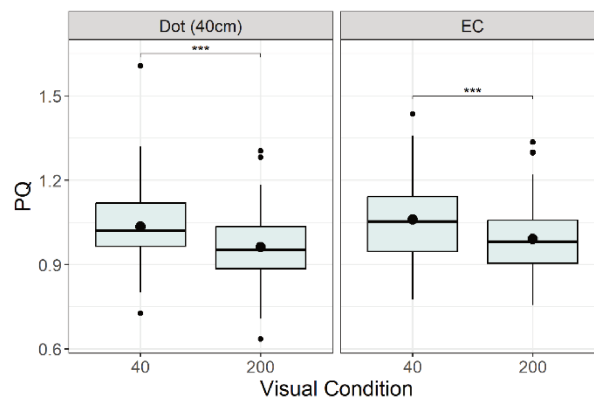


Figure 53: Plantar Quotient under situations A and B

- **Effect of foam and vision on Romberg Quotient**

Descriptive statistics were computed into table 9.

Table 9: Mean \pm SD, Median \pm IQR and IC_{95%} for RQ under 3 visual conditions (EO, Dot and Dot + image) and 2 podal (CT and Depron®)

	Romberg Quotient					
	Control		RQ _{Dot}		RQ _{Dot+image}	
	CT	Depron®	CT	Depron®	CT	Depron®
	40 cm					
Mean \pm SD	1,4 \pm 0,266	1,46 \pm 0,264	1,41 \pm 0,276	1,44 \pm 0,251	1,41 \pm 0,294	1,53 \pm 0,288
Median \pm IQR	1,37 [0,337]	1,45 [0,355]	1,43 [0,388]	1,44 [0,381]	1,4 [0,317]	1,54 [0,357]
IC _{95%}	[1,34 ;1,46]	[1,40 ;1,52]	[1,35;1,47]	[1,42;1,55]	[1,34;1,48]	[1,46;1,60]
	200 cm					
Mean \pm SD	1,23 \pm 0,170	1,16 \pm 0,174	1,22 \pm 0,172	1,19 \pm 0,185	1,28 \pm 0,206	01,25 \pm 0,230
Median \pm IQR	1,20 [0,201]	1,16 [0,210]	1,24 [0,242]	1,17 [0,271]	1,26 [0,206]	1,21 [0,295]
IC _{95%}	[1,19;1,27]	[1,12 ;1,20]	[1,18;1,26]	[1,15; 1,23]	[1,23 ;1,32]	[1.20 ;1,31]

To evaluate the influence of the visual conditions on the CoP measurements, we computed the RQ with different visual conditions.

We have a classic RQ (eyes closed/eyes open), and a RQ_{dot} (eyes closed/dot) and a RQ_{dot+image} (eyes closed/(dot + image))

There was a significant effect of the distance to the wall and vision on RQ as shown on figure 54 (resp. $F(1,75) = 89.23$, $p < 2e-14$, $\eta^2 p = 0.54$ and $F(2,150) = 12.89$, $p < 6.08e-6$, $\eta^2 p = 0.15$). There was a interaction effect between distance to the wall and foam conditions ($F(1,75) = 14.99$, $p < 0.0002$, $\eta^2 p = 0.17$) and a small one between foam and vision conditions ($F(2,150) = 4.48$, $p = 0.013$, $\eta^2 p = 0.06$).

Post hoc analysis showed a significant difference between 40 cm to the wall and 200 cm to the wall ($t(225) = 9.45$, $p < 0.0001$) with lower values when the wall was at 200 cm, but also between “dot + image” conditions and EO and “dot” conditions (resp. $t(150) = -4.71$, $p < 0.0001$; $t(150) = -4$, $p = 0.0003$) with higher values for “dot + image” condition.

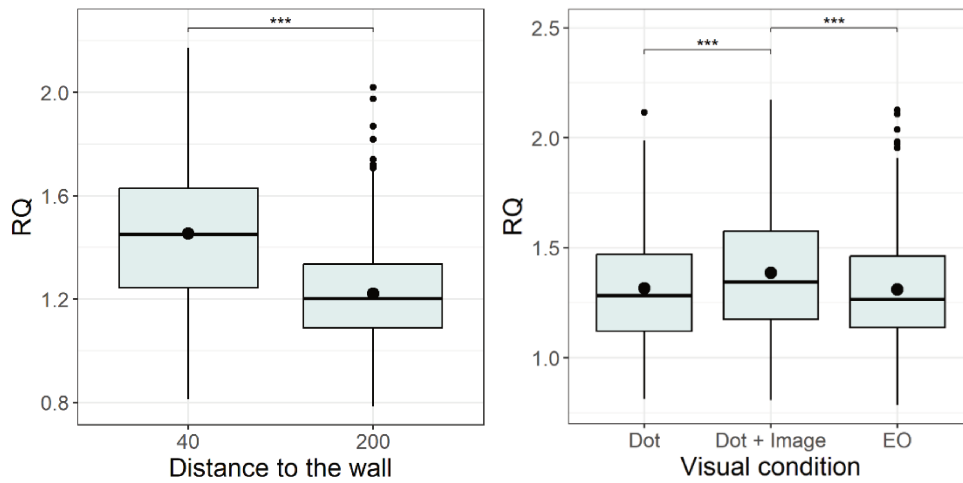


Figure 54: Romberg quotient under 3 visual conditions, and 2 wall distances

We computed RQ_{Dot} with the A situation, under 2 plantar conditions (CT and Depron®):

- Distance to the wall: 40 cm – Visual target: Dot at 40 cm
- Distance to the wall: 200 cm – Visual target: Dot at 40 cm

A situation

The repeated measures Anova did not highlighted a significant effect of the wall distance or the foam conditions on RQ (resp. $p=0.21$ and $p=0.09$) when there was a dot in front of the participant (Figure 55).

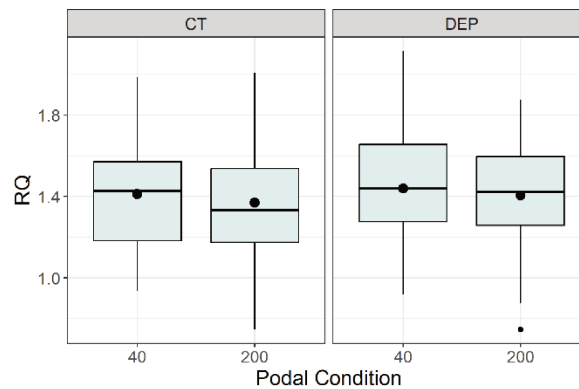


Figure 55: RQ in A situation with 2 podal conditions

C. Discussion

We were interested in evaluating the effect of different visual conditions on postural control in healthy adults, in order to understand which parameters, influence the static balance and its possible interaction with a foam ad information under the feet. The objective of this study was to gain a better understanding of how visual information impacts static balance, particularly when

standing on foam surfaces. To compare ourselves with the literature and a previous study (referred to as "Study 1"), we used a 6mm thick Depron® pad and distance to the wall from Foisy and al. (2017).

First, to be include in this study, it was necessary to performed optometrist tests. To have 76 adults with a physiological vision, 145 participants were recruited. It is 47% of this population who have no knowledge of this non physiological vision. The condition of inclusion is rarely implemented in the literature. Participants are asked if they have an ocular pathology, in which case they are excluded from the study. This high percentage raises questions about the uniformity of the studied populations. Indeed, the majority of excluded individuals had deficits in accommodation, visual acuity, or vergence, but were unaware of it. A vergence deficit or a low acuity appears to impact postural control on pathological population (such as dyslexic children or adults with vergence disorders) (Bucci et al., 2014; Morize & Kapoula, 2017; Uchiyama & Demura, 2008). Similarly, reduced visual acuity challenges postural control (Sambit et al., 2012). We do not know if the percentage of exclusion is normal or not. The assessment was conducted by professionals using specialized equipment which requires collaboration with them for further in-depth analyses of the impact of accommodation, visual acuity, or vergence deficits on static balance.

The distance between the participant and the wall induces a modification in static balance, with better control observed at shorter distances. This result is obtained regardless of the visual condition provided, whether with or without foam pads under the feet. When the participant has their eyes open without a target, the visual flow is providing a more precise assessment of their self-motion. The closer they are to a wall, the more the wall provides an indication of the oscillations performed. Not all protocols have the same distances between the wall and the participant, and the specific distance at which the optic flow is perceived and impacts static balance is not precisely defined. Moreover, the impact of visual flow on an individual's statics is dependent on the individual (Redfern et al., 2001; Stoffregen, 1985, 1986). In fact, even in healthy adult subjects, the capacity for static adaptation is individual, and the utilization and consideration of the environment will also be individual. As a result, comparing results across studies is challenging. Exploring the contribution of this distance and visual information in multisensory integration is warranted due to differences in protocols and the personal capacities of participants. As participants' intrinsic capabilities will also influence the perception of this flow, the lack of evaluation of this capacity further complicates the synthesis of results from the literature.

It appears interesting to also investigate the "cognitive" role of the presence of the wall. The situation with the target located at 40 cm and the wall at either 40 or 200 cm provides valuable insights on this matter. In the situation where the eyes are closed, we observe a difference in oscillation. Without visual information, it appears that the presence of a nearby wall enhances static control. We can assume that visual memory informs the participant about the distance to the wall, thus eliciting similar static balance control reactions as when they have their eyes open, albeit with an overall increase in oscillations (Bigel & Ellard, 2000; Tatler & Land, 2011). We can hypothesize that the risk of collision with the wall increases the reliance on cognitive control by the individual. The same result is observed when the target is at 40 cm. The vergence control induced by the target is therefore overridden by the distance information provided by the wall. Therefore, in the multisensory integration of this study, it appears that the distance between the wall and the participant is the predominant factor in static control (Calvert & Thesen, 2004).

The various targets presented to the participants allowed for a more precise characterization of the visual information utilized in static balance. As a reminder, the visual factor had four levels: eyes closed, eyes open without target, a round target (Dot), and a round target embedded within a landscape image (Dot + image). The static balance is improved when a textured target is placed in front of the participants. Compared to a Dot target, the texture in the image appears to provide information contributing to balance. The texture of this target enhances the perception of visual flow and allows for better self-evaluation of one's movement by the subject. However, we were unable to confirm whether the eyes were solely fixated on the red dot. It is possible that the presence of an image prompts the participant to explore it, leading to increased cognitive control, even if the task required participants to fixate on the red dot in the image, tracking eye movements would enable verification of compliance with the instruction. Additionally, this image was positioned on a white wall, creating high contrast between the image and the wall. This resulted in both vertical and horizontal information being provided to the participants through the contours of the image. The vertical information is utilized by the visuo-vestibular system to readjust the perceived vertical orientation to the gravitational vertical (Dyde et al., 2006; Kwon & Yeo, 2020). Providing an image the size of the wall would likely be a solution to mitigate this effect.

If we analyze the effect of a foam pad on the participants' statics in this study, the results obtained do not demonstrate any impact of Depron® on static balance. When calculating the PQ, a higher score is found for the textured target, which is in line with the previously presented results regarding the visual impact.

If we compare study 1 and 2 results on PQ (with eyes open and eyes closed, on Depron®) we obtain on the mean \pm standard deviation respectively $PQ_{Study1} = 1.02 \pm 0.133$ and 1.03 ± 0.138 (1 meter away from the wall), $PQ_{Study2} = 1.01 \pm 0.129$ and 1.06 ± 0.148 (40 cm away from the wall), and $PQ_{Study2} = 1.05 \pm 0.140$ and 0.991 ± 0.126 (200 cm away from the wall). The confidence of interval at 95% is respectively [0.993 ;1.04] and [1.00 ;1.05] for Study 1, [0,98 ;1,04] and [1,03 ;1,09] for Study 2 with a 40 cm from the wall and [1,02 ;1,08] and [0,962 ;1,02] with 200 cm. The results are of a similar magnitude. The use of plantar information for maintaining balance in subjects does not appear to be disrupted by the interposition of foam as all the PQ are around 1. We obtain a similar distribution with no evident sub population highlighted for all the calculated PQ (Figure 56).

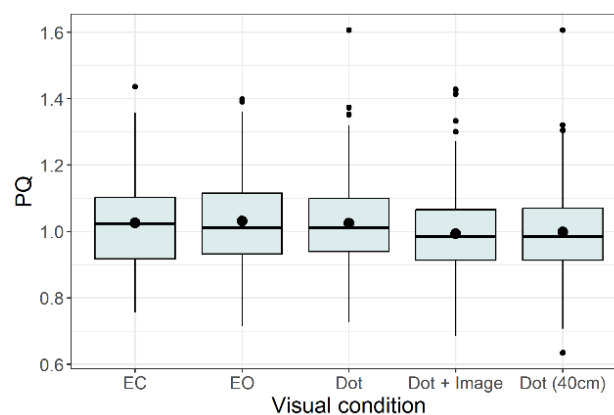


Figure 56: PQ computed under different visual conditions in study 2

However, we do observe that the interposition of foam affects static balance considering 2 distances to the wall but one visual information (dot at 40 cm). The impact of wall distance appears to be reduced when foam is interposed, which we did not find when both the target and the wall were at 200 cm. We observe a higher plantar quotient when the wall is at 40 cm, indicating that the length of the CoP on the foam pad is farther from that in the control condition. This suggests that the foam pad disrupts static balance more significantly when a target is placed at 40 cm. It is possible that this situation demands increased attention and allows for an amplified expression of the foam's effect. We find the same result with eyes closed. This supports the idea of environmental memory and its impact on the static oscillation of subjects.

In conclusion, the experimental conditions have indeed influenced the measurements of static balance in particular, the provided visual environment. The lack of standardization in the literature regarding the provided visual information makes it challenging to objectively assess the disturbance. One can assume that the sensory information provided is utilized following the following hierarchy: optic flow with the distance of the wall, ocular vergence with the targets, and plantar information with the foam pad. The vergence induced by the target, coupled with the increased visual flow, allows for better stability through enhanced utilization of the provided information. Depron® pad challenges static balance when the environment is nearby the participant (40 cm). It seems that to observe an effect of foam on the statics of healthy subjects, participants need to be placed in a balance challenge situation. While this information informs us about plantar information integration, it is not ecologically valid and does not reflect the challenges of daily life.

Ultimately, the significance of optic flow in this study raises a new question about the participants' ability to utilize this flow. While we controlled for the visual capacities of the participants, we did not assess their dependence on optic flow. This visual dependence refers to a person's reliance on visual information to maintain balance and orientation in their environment. The next study will help us better understand if our results are related to this dependence.

Study 3: Visual field and Plantar quotient

A. Introduction

During the first two studies, we were able to observe the significance of the provided visual information in maintaining balance. The visual system plays a significant role both in static balance and during movement (Davlin-Pater, 2010). The visual dependence suggests that a person relies more on visual cues than on other sensory inputs, such as proprioception or podal information, while maintaining static balance. It is linked to various aspects of motor control, such as task attention and implemented balancing strategies. In the case of non-functional systems, visual dependence helps identify individuals who will preferentially use visual information for compensation. Multisensory integration depends on the individual's intrinsic capabilities and their environment (Nyborg, 1971a, 1971b). Some individuals with a high degree of visual dependence may experience difficulty with balance and orientation when visual information is limited or disrupted. On the contrary, some individuals have no difficulty in maintaining their stability even when visual information is limited or absent. They have a low degree of visual dependence (Isableu et al., 2003). The objective of this study is to complement the previous one by observing if participants with visual dependence face increased difficulty while standing on a foam pad with their eyes closed.

Evaluating visual dependence typically involves assessing how much an individual relies on visual cues for balance and orientation compared to other sensory inputs (Jacobson, 1966). It is possible to conduct clinical tests or measurements on a platform to assess the dependence (Torneke, 2010). On force platform, the Romberg Quotient provides insight to this assessment. The higher the quotient, the greater the dependence (Black et al., 1982). The SOT (Sensory Organization Test) is a clinical test used to assess how an individual integrates visual, proprioceptive, and vestibular information to maintain balance (Ford-Smith et al., 1995; Peterka & Black, 1990; Riley & Clark, 2003). It involves standing on a force plate while various sensory inputs are manipulated. The Rod and Frame Test assesses a person's ability to align a tilted visual frame to their perceived vertical while seated in a dark room (Bagust et al., 2005; Dyde et al., 2006). The test typically includes multiple trials with varying degrees of tilt for both the rod and the frame (Oltman, 1968). The angles at which the rod and frame are tilted independently create different perceptual challenges. Results are based on the individual's ability to accurately align the rod with their perceived vertical despite the tilted frame. The degree of deviation from true vertical provides insights into their visual dependence or their reliance on visual cues for orientation. Individuals who are more visually dependent may find it more challenging to accurately align the rod with their perceived vertical when the frame is tilted. Their responses may show a greater deviation from the true vertical, indicating a higher degree of reliance on visual cues.

This test is typically performed while seated. However, in the case of our study, participants will be standing. Indeed, the use of sensory inputs depends on the task at hand. The assessment of visual dependence here is conducted on subjects who participated in Study 2. This test appears to be correlated with the movement of the center of pressure when the subject is facing a visual target (Kitamura & Matsunaga, 1990). The objective is to better understand the impact of visual

information on the static posture of healthy individuals with foam pads placed under their feet. During this test, the subject faces a square oriented at 28° either clockwise or counterclockwise. In this square, the rod that needs to be aligned vertically is oriented at 18° or -18° . Both the rod and frame are yellow in a dark environment (black wall).

Our hypothesis is that the previous scores obtained on the Plantar Quotient with eyes closed will be correlated with visual dependence. Indeed, the removal of visual information, combined with the foam pad, increases the balancing difficulty for visually dependent individuals. Conversely, non-dependent subjects would have a low Plantar Quotient with their eyes closed.

B. Material and method

B.1. Participants

We asked the 76 participants from Study 2 to participate to Study 3. We obtain 58 positive responses. One of the participants had a wrong comprehension of the task (abnormal results) and was taken off the analysis.

B.2. Experimental design

- Virtual environment

The RF test was developed with the Unity 3D game engine and displayed in a wireless HMD (Meta Quest 2) with a resolution of 1832×1920 per eye and a refresh rate of 90 Hz (<https://www.meta.com/fr/en/quest/products/quest-2/tech-specs/>) (Figure 57). The virtual yellow rod and frame were located at 80 cm in front of the participant's position within a virtual room. An anti-aliasing procedure has been applied to give a smoother appearance to the graphics. A manual controller was used to rotate the rod according to the direction of pressure applied to the joystick. The rod turned clockwise when the participant pressed the joystick to the right, and conversely. The rotation precision was $5^\circ/s$. At each trial, the participant validated the rod's orientation by pressing a trigger button on the manual controller.

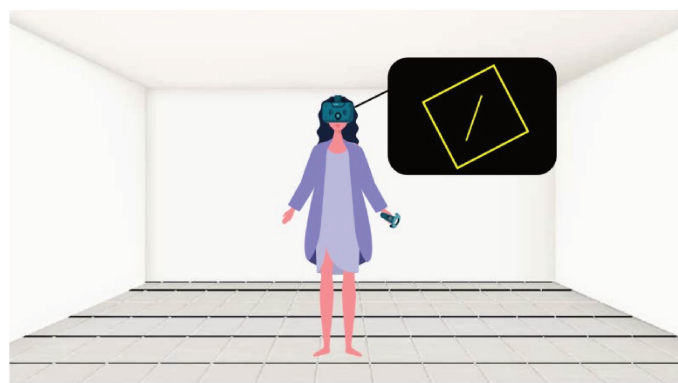


Figure 57: Illustration of the Rod and Frame Test with a participant wearing a wireless HMD

- Rod and Frame Test (RFT)

Our study aims at comparing field dependence considering podal information. The RFT was done with the virtual reality headset. The environment was a black wall in front of the participant with yellow rod and frame.

The frame was oriented at approximately $\pm 28^\circ$, and the rod at approximately $\pm 18^\circ$, creating four conditions (Figure 58):

- a. Frame 28° + Rod 18°
- b. Frame 28° + Rod -18°
- c. Frame -28° + Rod 18°
- d. Frame -28° + Rod -18°

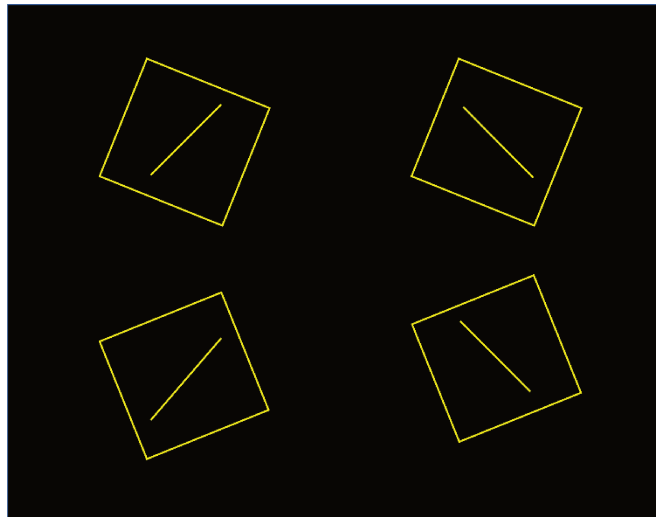


Figure 58: Rod and frame angulations associations in the RFT

The frame was adjusted to the participant size and 80 cm away from the participant.

- Foam Pad

As we want to compare this study to literature and our previous results, we chose Depron® (6mm thick).

- Testing procedure and factors

We used a repeated measure design. Participants were asked to stand while wearing the virtual reality headset and a controller (Figure 59). They had 4 non recorded trials to familiarize oneself with the tool and the task to be performed. We considered the following factors:

- Foam (2): control condition (no foam), Depron®. Foams were located under their bare feet.
- Vision (4): 4 rod and frame associations

A condition corresponded to a combination of the different levels of the foam and vision factor. Two trials were performed for each condition. In total participants performed 16 trials (2 repetitions * 4 vision * 2 foams), in a randomized order.

A training session of 4 trials was carried out before the test phase of 16 trials. In total, the participant spent approximately 10 minutes in the immersive virtual environment.

Foams were changed between each trial.

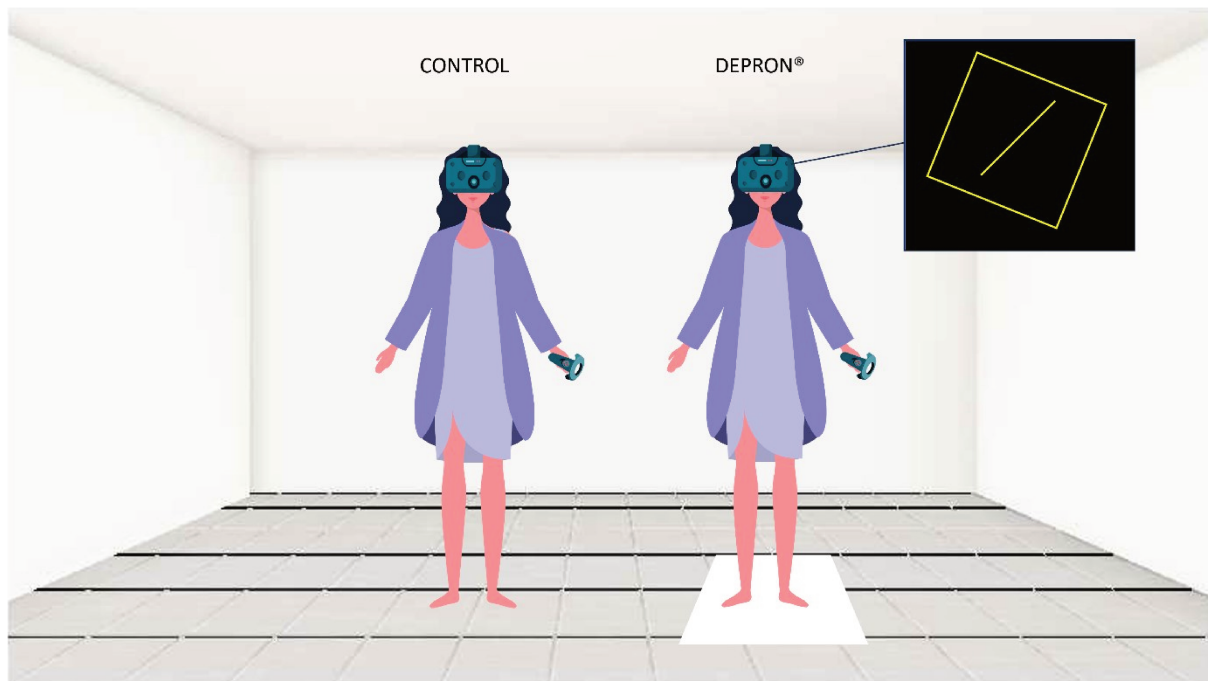


Figure 59: Illustration of the environmental conditions for the Rod and Frame Test

B.3. Data analysis

- Dependent variables

In order to determine if the visual field is correlated with the foam pad interposition, we first calculated the Absolute mean error for each trial. The error is the angle ($^{\circ}$) between the position of the Rod and the gravitational vertical.

- Statistical analysis

Statistics were performed using Jamovi® and R softwares. Level of significance was set to 0.05. Normality was assessed using the Shapiro-Wilk test. We performed a linear regression to evaluate the relationship between the PQ eyes closed obtained in static balance (Study 2) and measures of visual field dependence (RFT). For these simple linear correlations, we examined the sign of the regression equation and R^2 values were used to determine correlation strength. We also performed a repeated measure Anova between the podal factors (control and foam).

B.4. Results

- Descriptive statistics

Table 10 presents the Absolute Mean Error at the RFT with or without foam under the feet.

Table 10: RFT descriptive statistics

	Rod and Frame Test	
	Control	Depron®
Mean ± SD	1,7 ± 3,16	1,78 ± 3,79
Median ± IQR	1,05 [1,25]	1,02 [1,23]
IC _{95%}	[1,32 ;2,14]	[1,29 ;2,27]

- Effect of podal condition

Du to non normal distribution we did a Friedman test to compare the 2 conditions on RFT (control and Depron®). No significant difference was highlighted between the 2 conditions (p=0.469).

- Correlation between RFT and Plantar Quotient

We did not highlight any correlations between the PQ eyes closed (either at 40 cm nor at 200 cm from the wall) and RFT (resp. $R = -0.066$, $R^2 = 0.0044$, $p = 0.625$, and $R = 0.172$, $R^2 = 0.0296$, $p=0.201$) (Figure 60).

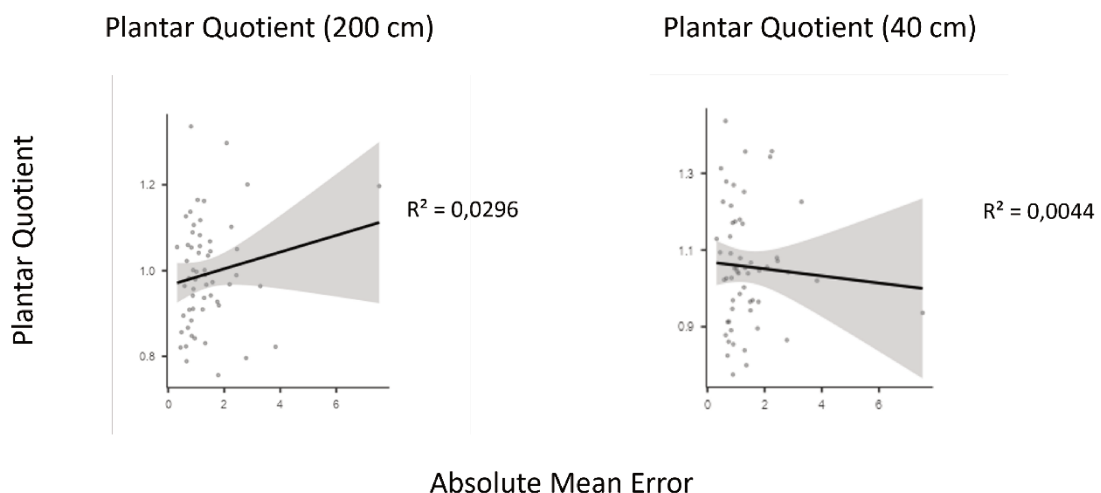


Figure 60: Correlation between plantar quotient from Study 2 and Absolute Mean Error from RFT test

C. Discussion

The objective of this study was to determine whether the plantar quotient and visual field dependence were correlated. As a reminder, our study population consisted of healthy adults (aged between 18 and 45 years) whose orthoptic assessment was within physiological norms. We had hypothesized that participants with a higher degree of visual field dependence would experience increased difficulty when standing on a foam pad with their eyes closed. An increase in the plantar quotient would have been correlated with visual field dependence with a significant positive correlation. The results did not highlight any correlation between those 2 parameters, neither at 410 cm nor at 200 cm distance from the wall.

We also compared the RFT between 2 podal conditions: control (i.e., no foam) and Depron®. No significant difference was highlighted. This result is consistent with the findings obtained in Study 1 and 2: The use of Depron® does not pose a stabilization challenge for the studied population. Its capacity for multisensory integration is sufficiently high to avoid any difficulty. It appears that despite visual field dependence in some individuals, the information from other subsystems is sufficient for their geocentric reference to be accurate. However, it is possible that the result may be different in an older or pathological population where sensory weighting is altered due to the diminished sensory capabilities of the participants (Hafstrom et al., 2004; Lopez et al., 2006; Lord & Webster, 1990). Furthermore, our expertise is not specific to the visual field, and this study aimed to open up potential new experiments. Methodological biases should be noted, including the likely insufficient number of repetitions and the use of a single evaluation test for the visual dependence. Our choice was guided by the possibility of conducting this test in clinical routine. However, a more detailed analysis with other tests is necessary to draw more conclusive conclusions. However, it appears necessary to take all these visual information into account before drawing conclusions about the static balance of our patients placed on thin foam pads.

Chapter 2 Discussion

The objective of this chapter was to gain a better understanding of the assessment conducted by the plantar quotient and its potential interactions with the environment. Our objective was to establish norms within a healthy population in order to identify non-physiological static balance.

The choice of foam is a subject that needs further exploration. Indeed, we chose to confront the reality of clinical practice. However, it is possible that this choice may not be optimal for assessing the role of plantar cutaneous information in this balance evaluation. This requires more technical information about these foams and, therefore, collaboration with materials analysis laboratories. The chosen thickness is, of course, subject to discussion. The height used in this clinical practice is far from the foam heights found in the literature (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; B. Liu et al., 2018; Patel et al., 2008). While our foam thickness is less than a centimeter, the authors in the literature commonly use foams with a minimum thickness of several centimeters. The difficulty in static balance is therefore increased, resulting in significantly higher plantar quotients. In these studies, sensory reweighting is different, with a more alerting proprioceptive information. Isolating only the plantar cutaneous system appears to be impossible or it requires a coupled analysis between plantar and proprioceptive information to determine which foam affects the systems and to what extent. The hardness and elasticity of the foam should also be taken into account. If the foam has low hardness, the weight placed on it will compress the material more. If its elasticity is high, during oscillatory movements, the foam will return to its initial shape between two supports. The return to the initial shape or lack thereof can potentially alter the future response because it changes the plane on which the individual is positioned. We did not take into account the weight of the participants in our analysis. However, the thicker the foam, the greater the impact of the compression of the foam between two subjects of different weights. To our knowledge, this weight is not considered in the choice of foam for calculating the PQ in clinical settings.

So, our results are based on a thin foam of 6mm thickness. Its impact on static balance can be considered negligible in a healthy adult population. Indeed, QP between 0.99 and 1.02 are observed when no visual information is provided unless a white wall. An environmentally friendly alternative to Depron® could be proposed because our results obtained with Orthomic® are similar. However, experimental conditions such as the distance to the wall and visual information impact the results of healthy subjects. We notably observe differences between the 2 distances to the wall conditions with a dot at 40 cm. The subject's awareness of the distance to the wall alters their balance. 40 cm can be considered as personal space violation (Hecht et al., 2019). Furthermore, the persistence of this difference with eyes closed indicates the participant's integration of the environment. Visual information is a major element of both static and dynamic control. Its removal coupled with the presence of a nearby obstacle can certainly induce a state of stress and increased control of one's static balance. While the objective of this work is to identify

the characteristics of the PQ and the impact of its environment, one must consider the clinical evaluation as a whole. A clinical evaluation should take into account the patient's daily life in order to understand the impact of a deficit on their daily routine (Korman et al., 2016). Personal space shape and size is individual dependent. 45cm distance is considered as intimate while 45 to 120 cm is personal zone (Neggens et al., 2022). It is unlikely that an evaluation at 40 cm from a wall represents a clinically relevant situation. However, this distance does allow for a better assessment of sensory weighting. Indeed, differences are also observed in the oscillations of participants with their eyes open. In this situation, the information from the wall is present, and they are more capable of taking it into account regardless of their visual dependence. As soon as a visual target is added, differences between the conditions become more pronounced. Visual targets at 40 cm will induce forced ocular vergence. Textured information in an image also enhances the perception of visual flow. The lack of standardization in static evaluation in the literature or the limited information in studies makes it difficult to compare results across different studies. To enable comparisons of a patient's progress over time, it is therefore necessary to standardize their measurement environment within the clinic. A change in scenery or the platform's positioning relative to the wall can result in differences in the obtained results that are not solely due to changes in an individual's capabilities. Furthermore, if healthcare professionals want to be able to discuss their results in this analysis, it is essential to establish standardization in order to compare data. The fact that QP is larger with specific visual information indicates the role of vision in static balance. The use of visual information is therefore preferred under these conditions. Since Depron® does not appear to have a significant impact on all the analyses conducted, regardless of the chosen distances or targets, the results in the literature may reflect more an ability to integrate visual information rather than plantar information. If not, let's take a closer look at the results of Foisy et al. (2017). The QP and QR appear to exhibit similar characteristics (no data overlap between the two subpopulations described: plantar exteroceptive inefficient or efficient). The results of our two studies (1 and 2) do not allow us to identify two distinct subpopulations. On the contrary, the vast majority of individuals have a 95% confidence interval for the mean QP ranging from 0.995 to 1.02. Furthermore, the choice of the variable used for calculating QP alters the linear distribution of participants. To better understand if the PQ is linked to the integration of an orthotic element (Chapter 3), we chose a situation without additional visual information to avoid its impact on our results.

The choice of the variable used for QP is also a topic for discussion. Our choice was based on two factors: the stability of the measurement across repetitions and among participants, while also considering the practicality of real-world conditions. Experimental conditions are often non-ecological, and few podiatrists perform three repetitions of each foot condition they test. In this context, the length of the CoP displacement (or its velocity) seems like interesting parameters. However, a more comprehensive analysis of patients' static balance capacity would likely involve combining multiple parameters to define a more precise profile. In this regard, the platform used in the studies in Chapter 2 is a platform commonly found in podiatry clinics. Currently, the software does not offer a coupling of certain CoP parameters.

While we have considered real clinical conditions, another possibility to assess the significance of this plantar information on stabilometry platforms should be considered. Typically, to evaluate the weight of sensory information, it is either stimulated or diminished. The use of textured material on a platform can also be employed (Aruin & Kanekar, 2013; Ma et al., 2016; Park et al., 2021).

This material consists of small indentations (whose diameters and thickness may vary in different studies). They are distributed on the surface of the material and act more like stimulation points. Indeed, on these support zones, the pressure exerted would be increased by the indentations, leading to greater stimulation of mechanoreceptors. Texture materials improve static balance (Kenny et al., 2019). The combination of this material with eyes closed results in better stability than without this plantar stimulation. This condition allows room for plantar information to express, as we know that visual information is predominant in both static and dynamic control (Davlin-Pater, 2010). However, the results also show differences in the choice of textured materials and the parameters of the CoP analyzed. We also do not have all the details of the environment (visual and distance to the wall). While they alter the results when foam is interposed, is the weight of visual information the same when mechanoreceptors are stimulated with textured materials? More studies are therefore needed before standardizing a PQ on textured materials. However, the ecological aspect is also worth discussing. At the moment, few material suppliers offer this type of material (only one to our knowledge) in France as a sole covering for insoles.

If we focus on the participants and their characteristics, obtaining a homogeneous population is particularly challenging. Visual acuity appears to be an important point for discussion. Indeed, few studies on static balance on foam pads include optometric analysis of participants. Our mistake was underestimating visual deficits in a population of young adults and their lack of awareness of them. A nearby visual target will require an effort of convergence, while an image will require accommodation. Do defects in these two parameters, for example, influence the results in a healthy population? We know that when the studied population has significant visual deficits, the balance strategy is altered, and static balance is affected (Bednarczuk et al., 2021). Podiatrists are not vision specialists and may not be proficient in conducting vision tests or interpreting their results. However, they should consider that their results are influenced by the patient's capabilities, especially when conducting analyses over time. Our analysis of visual dependence is not sufficiently relevant to be considered a reliable result. Future studies are needed. However, the implementation of this test in virtual reality is straightforward and could enable analysis in a clinical setting. Just like other modified parameters, this dependence does not seem to pose a challenge for participants when they are on foam. Aging also leads to difficulties in static balance. We could have also subdivided our population or considered different age groups to obtain norms within these categories.

Finally, considering the patient in their entirety constitutes the biopsychosocial model. This model involves taking into account the individual's history, knowledge, and psychological state, rather than solely focusing on the collected physical data (Borrell-Carrió et al., 2004). This model can explain variabilities within a population that is considered physiologically homogeneous (Hulla, 2019). This work is anchored in the field of health, and the consideration of the individual within a broader sphere appears interesting and allows for a more specific and individualized approach to care.

In the next chapter, we will move further on the role of podiatrist considering their intervention through the use of insoles elements. We will then propose to evaluate the integration of an orthopedic insole element, based on the PQ results obtained in Study 1. Indeed, PQ has been described as predictive of the ability to integrate plantar information. Therefore, we have selected three subpopulations with different PQs. Our analysis will focus on integrating the insole both in

static and dynamic conditions to provide a more ecological analysis of daily life conditions, specifically during walking.

Chapter 3: Evaluation of a thin orthopedic on static and dynamic task

Chapter 3 will present 2 studies. The first is evaluating foot orthoses insert on static and gait analysis. The 2nd is linked to Chapter2, Study3: in this chapter, participants were selected in the Study 4 population.

Study 4: Orthopedic element effect on static and gait

A. Introduction

Orthopedic insoles are utilized by podiatrists to rectify or enhance the functionality of the foot and lower limb during weight-bearing (Barnett, 1998). They achieve this by introducing specific contours designed to provide novel input to the motor control system, consequently altering the proprioceptive and sensorimotor feedback transmitted (Becker et al., 2023; Hatton et al., 2013; Mihaela Alina & Corina, 2021). In clinical practice, the dynamic impact is primarily assessed during locomotor tasks such as walking or running.

The impact of orthopedic insoles is a subject of discussion in the literature. Indeed, there are numerous therapeutic approaches for various pathologies, and their assessment is diverse (Barton et al., 2010; Murley et al., 2009). Some findings indicate a reduction in pain following the use of insoles (Hawke et al., 2008). Additionally, there is evidence of alterations in lower limb muscle activity and a reduction in foot deviation, for instance (Alfuth, 2017; Barton et al., 2010; Christovão et al., 2013; Robb & Perry, 2022). In their study, Foisy and colleagues demonstrated a relationship between the integration of plantar information (as determined by the calculation of the plantar quotient) and the incorporation of an element within orthopedic insoles. The integration of an orthopedic insole element would vary based on the patient's oscillation result on a thin foam platform. They classify individuals with a plantar quotient below 1 as "plantar exteroceptive inefficient" and those with a higher quotient as "efficient" (Foisy & Kapoula, 2017). This result appears to indicate an individual physiological capacity for the assimilation of plantar information. However, it is important to note that this analysis was conducted solely during a static task. The element used is a medial arch support located within the plantar arch and measures 3 mm in height. When positioned bilaterally, it would induce changes in the oscillation area and the length of the center of pressure displacement. Its integration over time would modulate motor control after 7 days (Foisy & Kapoula, 2017; Tramontano et al., 2019). When used unilaterally, it appears to alter the position of the Center of Pressure (CoP) along the medio-lateral axis. Its insertion under one

foot would elicit a postural response due to the activation of mechanoreceptors, resulting in a contralateral shift to restore static balance (Janin & Dupui, 2009).

All these analyses with such thin elements have been conducted in static situations. However, this evaluation is far from daily life because wearing orthopedic insoles involves using them during movements such as walking. To visualize the impact of an orthopedic insole element on locomotion, several analyses can be conducted, including an assessment of lower limb angles, analysis of muscle activity, or examination of locomotor trajectory (Alfuth, 2017; Chen et al., 2010; Hajizadeh et al., 2020; Hatton et al., 2013; Jeleń et al., 2008; Mills et al., 2010; Nester et al., 2003). It is also possible to examine the movement of the CoP along its gait trajectory.

The aim of this study is to assess the effect of a thin orthopedic insole element positioned unilaterally on both static and dynamic balance. Participant selection will be based on their plantar quotient results to better understand if plantar integration on foam an effective indicator of the integration of an insole element in the two indicated situations is. The study of the CoP displacement will be conducted along both the mediolateral and anteroposterior axes, as well as the oscillation area and the length of CoP displacement. The analysis of gait will assess the effect on the mediolateral axis of the element compared to the participants' CoM projection. This analysis will include simple trajectories such as walking straight and making 90° turns to the left and right. It will specifically focus on the foot contact moment during the walking cycle and compare the areas between the displacement of the point located in the middle of the "toe-heel" axis and the CoM.

B. Material and method

B.1. Participants

This study relies on the sample of Study 1. The 60 participants were selected based on their QP and therefore are part of the 132 subjects who participated in Study 1. We divided the study 1 population into 5 groups based on the results obtained from the QP with eyes open on Depron® pad. Since the data is continuous, we selected groups 1, 3, and 5 (1 representing the lowest QP and 5 the highest) in order to avoid data overlap. We asked all selected participants to take part and set a quota of 20 people per group.

60 healthy adult participants (24 men, 36 women) volunteered for this study and gave their informed consent. They were 29.2 ± 9.32 y. o, 171 ± 9.22 cm tall and weighed 66.75 ± 10.43 kg. Participants should not have any balance disorders (inner ear, vision) and be taking any medication that can disturb balance. They must not have undergone a recent trauma of the lower limbs (less than 3 months or in the course of rehabilitation). Pregnant women and people above 59 years old were not included.

(Only 39 participants are presented in the results below)

B.2. Experimental design

This study is divided in 2 parts: a static and a dynamic evaluation.

- **Static Evaluation**
 - Instrumental

Force platform

Static measurements were taken on an AMTI® force platform measuring 600 x 1200 mm, with a data acquisition frequency of 960 Hz (Figure 61).

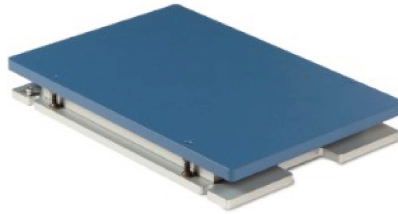


Figure 61: AMTI® force platform

Foot orthoses

Three pairs of orthopedic insoles were created (Figure 62):

1. Control Pair (CT): This pair consisted of a 1mm-thick resin base insole for both the left and right feet.
2. StimR Pair (StimR): In this pair, the right insole was composed of a 1mm-thick resin base along with a medial arch support element, while the left insole was made up of only a 1mm-thick resin base.
3. StimL Pair (StimL): In this pair, the left insole was made with a 1mm-thick resin base and a medial arch support element, whereas the right insole consisted of only a 1mm-thick resin base.

(The resin was “Thermofibre Bois” (Capron®, France).)

The medio intern element within an ovoid shape is located at the midfoot level. It measures 3mm in height.

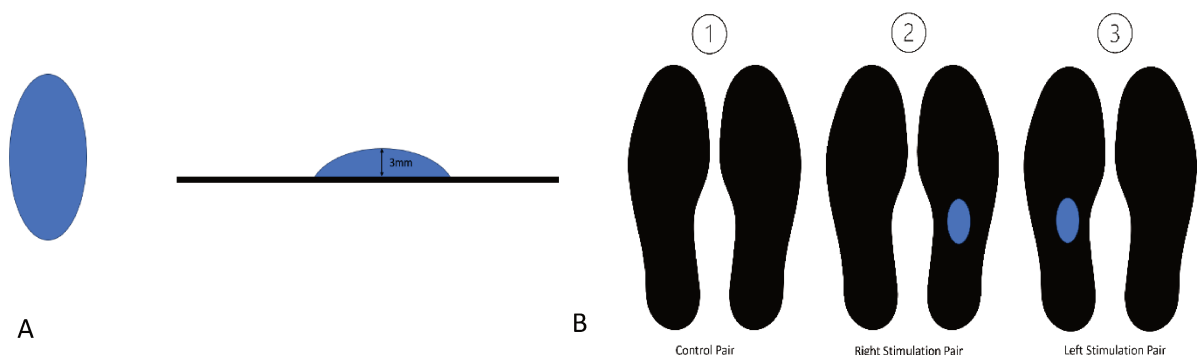


Figure 62: Foot orthoses. A: thin medio-intern insert of 3 mm high on the orthoses. B: 3 pairs of foot orthoses proposed: a control, a Right stimulation (StimR) and a left one (StimL)

Shoes

The recordings were made with gymnastics slippers (Decathlon®). Each shoe size included a pair of slippers, 3 pairs of foot orthoses (as explained below) (Figure 63).



Figure 63: Shoes used for the experimentation (Decathlon®)

- Environmental conditions

The experiment was conducted in the motion capture gymnasium of the M2S laboratory on the Ker Lann campus (Bruz) within the ENS (Figure 64).

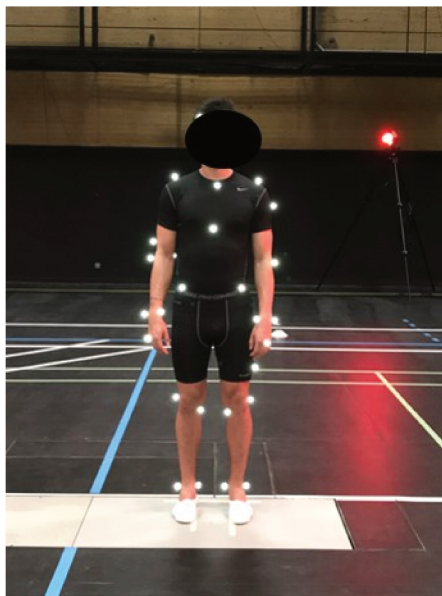


Figure 64: Environmental conditions of the static part of study 4

- Design

For the static evaluation, we used a repeated measure design. We considered the following factors (Figure 65):

- Foot (4): control condition (no foam), Depron®, Stimulation under the Right or the left foot. Foam located on the stabilometry platform.
- Vision (2): eyes closed or open

A condition corresponded to a combination of the different levels of the foam and vision factor. Three trials were performed for each condition. Between each trial, a rest time of at least 30s was imposed. In total participants performed 24 trials (3 repetitions * 2 vision * 4 foams), in a randomized order. A session lasted between 45 to 60 minutes. Foams were changed between each trial.

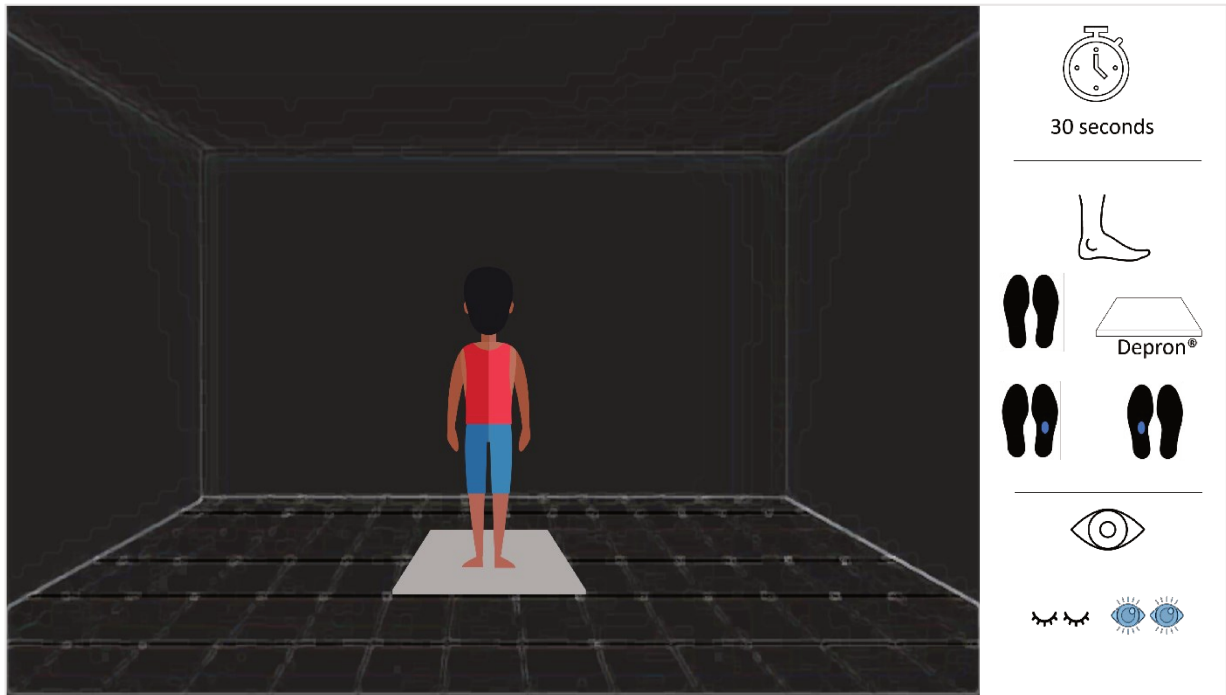


Figure 65: Environmental design of the Study 4 (Laboratory M2S)

- **Dynamic evaluation**
- **Instrumental**

The participants' movements during the locomotor task were recorded using the Qualisys® optoelectronic system. The system comprised 26 high-resolution infrared cameras (4 megapixels) operating at 120 Hz. To ensure the highest data accuracy, each participant wore a form-fitting outfit. 41 reflective markers were placed on standardized anatomical locations following the IBS standards (Wu et al., 2002, 2005). The same operator performed all marker placements to minimize variations in marker positions on the same subject.

- **Environmental conditions**

The experiment was conducted in the motion capture gymnasium of the M2S laboratory on the Ker Lann campus (Bruz) within the ENS. The walking surface represented a square of 9x9 meters. Colored markers (blue, white, red, and yellow) were placed at each corner, designating the starting and finishing points for participants throughout the experiment. 1-meter walking lanes were

marked on the floor, following the diagonal direction of the square, using tape, to standardize the starting and finishing positions and orientations of the participants (Figure 66).

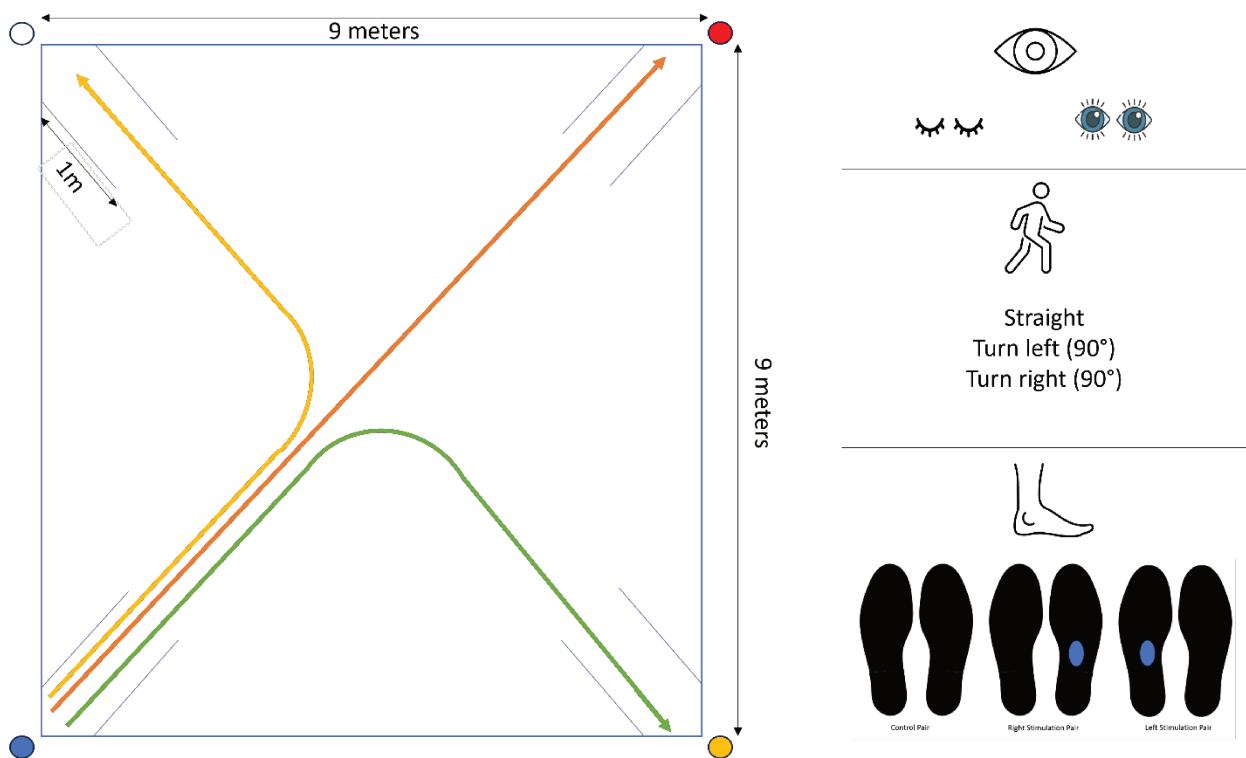


Figure 66: Experimental environment and conditions of Study 4

- Design

For the gait evaluation, we used a repeated measure design. We considered the following factors:

- Foot (3): control condition (no foam), Depron®, Stimulation under the Right or the left foot. Foam with the specific shoes.
- Vision (2): eyes closed or open.
- Gait (3): Straight, turn left (90°) and turn right (90°)

A condition corresponded to a combination of the different levels of the foot, vision and gait factors. Three trials were performed for each condition. In total participants performed 54 trials (3 repetitions * 2 vision * 4 foot * 3 gait), in a randomized order. A session lasted between 90 to 120 minutes.

B.3. Data analysis

- Dependent variables

In order to determine if standing balance was affected by foot orthoses interposition, we first calculated the surface of CoP oscillations and the length of CoP displacement. We computed the mean displacement of CoP and its standard deviation on anteroposterior and mediolateral axes for each trial. We compute the Plantar Quotient selecting length of CoP displacement on Depron®.

As the task was to maintain posture as still as possible, whatever the conditions used, the best value recorded among the 3 trials was kept for the analysis.

In order to determine if gait was affected by foot orthoses, we computed the CoM and projected its trajectory on the ground. We computed footstep positions on the ground. To obtain a complete curve, we interpolated those positions using a spline. Subsequently, we computed the areas between the footstep curves and the CoM curve (Figure 67). Subsequently, we calculated the ratio between the right area and the left area with the equation (5):

$$\text{Gait Ratio} = \frac{\text{Right Aera} + \text{Left Aera}}{\text{Right Aera} - \text{Left Aera}} \text{ (Equation 5)}$$

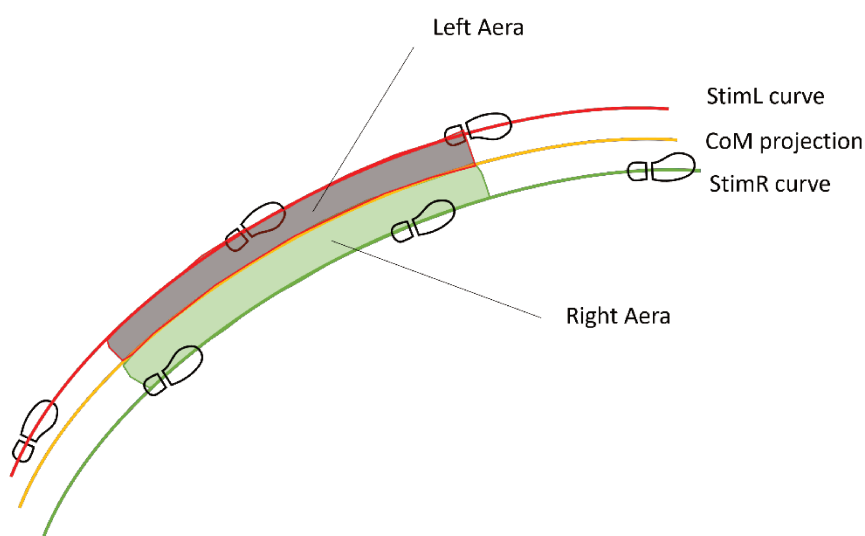


Figure 67: Illustration of the horizontal CoM trajectory, as well as the horizontal interpolated trajectories of the toe-heel segment center used to determine Gait Ration during locomotion.

- Statistical analysis

Statistics were performed using Jamovi® and R softwares. Level of significance was set to 0.05. Normality was assessed using the Shapiro-Wilk test.

For the CoP parameters, when the data were normally distributed, we performed a repeated measures Anova. If not, the non-parametric ART-Anova (aligned Rank Transformed) was used to evaluate main and interaction effects of plantar stimulation and visual conditions on dependent variables. Pairwise comparisons were performed as post hoc analyses using Durbin-Conover tests.

For the gait Ratio, when the data were normally distributed, we performed a repeated measures Anova. If not, the non-parametric ART-Anova (aligned Rank Transformed) was used to evaluate main and interaction effects of plantar stimulation, gait and visual conditions on dependent variable. Pairwise comparisons were performed as post hoc analyses using Durbin-Conover tests.

We performed a linear regression to evaluate the relationship between the PQ eyes open obtained in static balance (Study 1) and CoP parameters in static condition, and with Gait ratio, both with StimL or Stim R. For these simple linear correlations, we examined the sign of the regression equation and R² values were used to determine correlation strength.

B.4. Results

- **Descriptive statistics**

We computed tables with the mean, standard deviation, median and IQR and IC_{95%} on Length of CoP displacement, surface of CoP, mediolateral and anteroposterior position of CoP and their standard deviations (Table 11).

Table 11: Descriptives statistics of Study 4

	Surface						
	Control		StimR		StimL		
	EO	EC	EO	EC	EO	EC	
Mean ± SD	583,22 ± 53,86	585,75 ± 42,17	602,15 ± 45,82	574,81 ± 45,85	593,17 ± 56,07	575,51 ± 47,66	
Median ± IQR	587,12 [73,88]	591,05 [53,92]	603,04 [067,14]	576,01 [57,38]	591,39 [75,8]	574,59 [68,1]	
IC _{95%}	[569; 597]	[575; 597]	[590; 614]	[545; 587]	[579; 608]	[563; 588]	
	Length						
	Mean ± SD	54.7 ± 15.99	56.10 ± 21.00	62.1 ± 20.01	65.53 ± 19.90	62.15 ± 18.3	66.10 ± 20.60
	Median ± IQR	52.37 [15.58]	52.33 [16.06]	61.83 [22.80]	61.10 [24.61]	60.41 [26.82]	61.79 [22.2]
IC _{95%}	[50,6 ;58,8]	[50,7 ;60,5]	[56,9; 67,3]	[60,4; 70,7]	[57,4; 66,9]	[60,7; 71,4]	
	Mean position on anteroposterior axis						
	Control		StimR		StimL		
	EO	EC	EO	EC	EO	EC	
Mean ± SD	-190.89 ± 14.08	-189.64 ± 12.51	-194.08 ± 12.75	-188.13 ± 12.20	-193.27 ± 13.53	-187.6 ± 11.76	
Median ± IQR	-191.96 [19.68]	-190.09 [16.35]	-195.3 [18.98]	-188.07 [17.5]	-191.12 [19.94]	-185.87 [15.97]	
IC _{95%}	[-195; -187]	[-193; -186]	[-197; -187]	[-191; -185]	[-197; 190]	[-191; -185]	
	Standard deviation						
	Mean ± SD	1,47 ± 0,87	1,44 ± 1,1	1,47 ± 0,93	1,66 ± 0,85	1,47 ± 1,20	1,49 ± 1,00
	Median ± IQR	1,21 [1,31]	1,22 [1,19]	1,43 [1,18]	1,58 [1,28]	1,15 [1,02]	1,15 [1,55]
IC _{95%}	[1,24;1,69]	[1,16 ;1,73]	[1,23;1,71]	[1,44; 1,88]	[1,16 ;1,78]	[1.22 ;1,74]	
	Mean position on mediolateral axis						
	Control		StimR		StimL		
	EO	EC	EO	EC	EO	EC	
Mean ± SD	5.52 ± 7.12	6.93 ± 5.68	6.9 ± 6,5	5.55 ± 6.82	- 5.17 ± 7	-5.33 ± 7.55	
Median ± IQR	6.20 [8.24]	6.33 [7.65]	6.70 [7.66]	6.07 [7.85]	-5.10 [9.2]	-5.17 [12.39]	
IC _{95%}	[3,68 ;7,37]	[5,47; 8,40]	[5,22; 8058]	[3,79; 7,31]	[-6,98; -3,36]	[-7,28; -3,38]	
	Standard deviation						
	Mean ± SD	1,05 ± 1,00	0,9 ± 0,59	1,07 ± 0,76	1,52 ± 1,06	0,96 ± 0,63	1,36 ± 0,78
	Median ± IQR	0,75 [1,03]	0,72 [0,77]	0,87 [0,97]	1,2 [1,21]	0,85 [0,88]	1,18 [1]
IC _{95%}	[0,79; 1,3]	[0,75; 1,05]	[0,87; 1,26]	[1,24; 1,79]	[0,80; 1,13]	[1,18; 1,00]	

- **Plantar Quotient**

As the participants were selected based on their PQ from Study 1, we computed a new PQ based on their results on Depron® eyes open to verify our group distribution. The new distribution doesn't fit the previous one (Figure 62): PQ is not stable through time. As a reminder we had selected 3 sub populations with distinct PQ from Study 1.

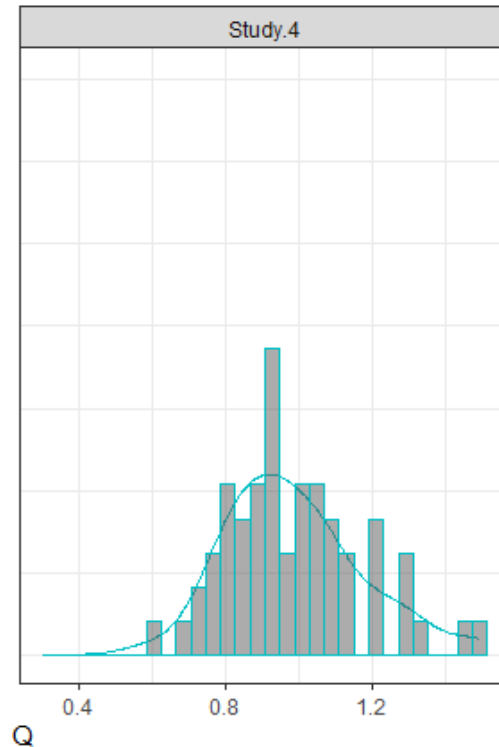


Figure 68: Plantar Quotient from study 4

We decided to take into account this new PQ to analyze the next parameters through correlations.

- **Effect of plantar stimulation and vision on CoP length and surface of CoP**

The ART-Anova highlighted a significant effect of Vision on Length of CoP displacement ($F(1.59) = 36.57$, $p < 1.08e^{-07}$, $\eta^2 p = 0.38$) and on Surface of CoP ($F(1.59) = 36.95$, $p < 0.001$, $\eta^2 p = 0.02$) with lower values eyes closed for the Surface of CoP. Post hoc analysis showed a difference between eyes closed and eyes open on length and surface (resp. $t(59) = -6.04$, $p < 0.0001$ and $t(59) = -6.08$, $p < 0.001$) (Figure 69).

The ART-Anova highlighted a significant effect of Plantar Stimulation on Length of CoP displacement ($F(2.118) = 23.76$, $p < 2.13e^{-09}$, $\eta^2 p = 0.29$) but no significant effect were highlighted on Surface of CoP ($p = 0.355$). Post hoc analysis showed a difference between control, StimR and StimL (resp. $t(118) = -5.82$, $p < 0.0001$ and $t(118) = -6.10$, $p < 0.0001$) with the orthotic stimulation making more perturbation on static stability than control condition (Figure 70).

Let us notice that we highlighted a small interaction between plantar stimulation and vision (on Length $p < 1.23e^{-08}$ and Surface $p < 0.001$, $\eta^2 p = 0.016$) with eyes closed less challenging than eyes open.

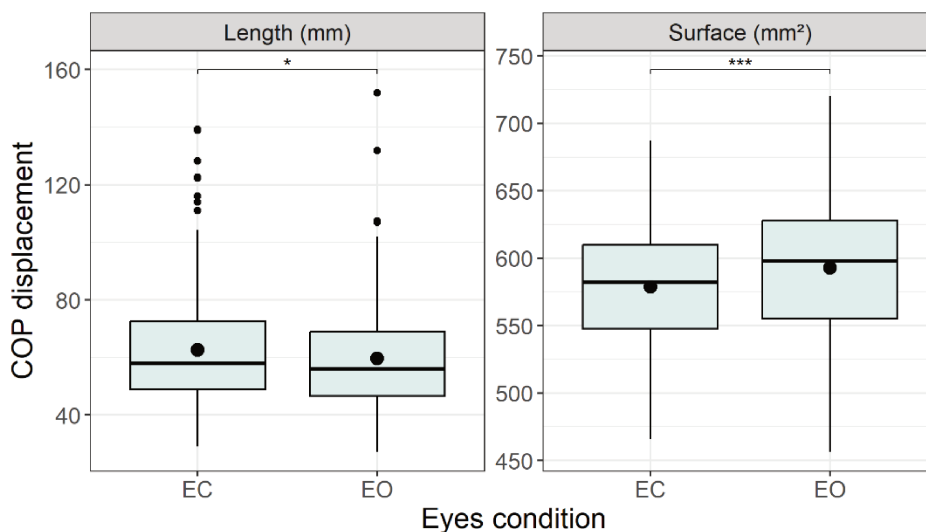


Figure 69: Length and surface of CoP displacement under 2 visual conditions

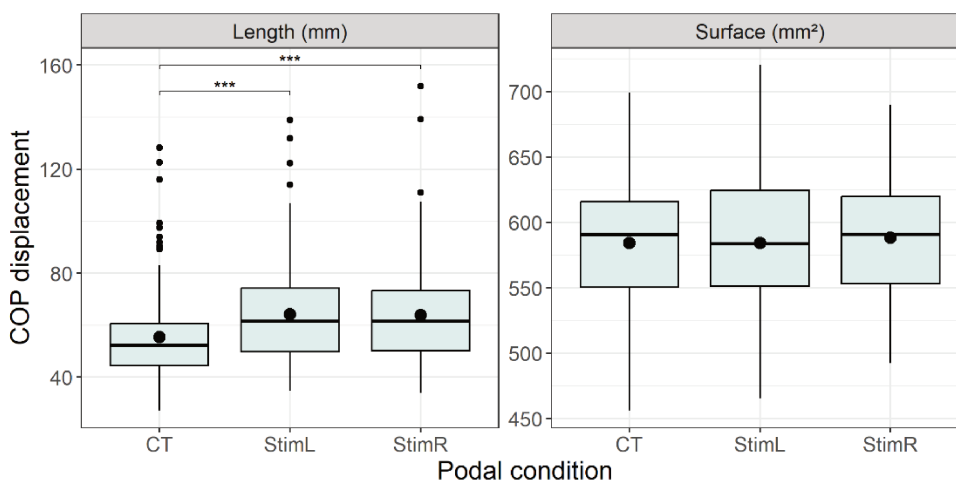


Figure 70: Length and surface of CoP displacement under 3 plantar conditions (Ct, StimR and StimL)

- **Effect of vision on CoP position and standard deviation on Anterio-posterior and medio-lateral axes**

The ART-Anova highlighted a significant effect of vision on anteroposterior position of CoP ($F(1.59) = 47.73$, $p < 3.86e^{-09}$, $\eta^2 p = 0.45$) (Figure 72) but no significant effect on CoP position on mediolateral axe ($p = 0.722$) (Figure 73). Post hoc analysis showed a difference between ($t(118) = -8.71$, $p < 0.0001$ for control and $t(118) = -68.69$, $p < 0.0001$ for StimR) with the orthotic stimulation on the left being more lateralized.

The ART-Anova did not highlighted a significant effect of plantar stimulation on anteroposterior position of CoP ($p = 0.37$) (Figure 71) but a significant effect on CoP position on mediolateral axe ($F(2.118) = 50.44$, $p < 2e^{-16}$, $\eta^2 p = 0.46$) (Figure 74). Post hoc analysis did not show a difference between EC and EO ($p = 0.72$).

The ART-Anova did not highlighted a significant effect of vision or plantar stimulation on standard deviation on the anteroposterior axe (resp. $F(1.59)=0.45$, $p=0.0002$, $\eta^2p=0.20$ and $F(2.118)=3.26$, $p=0.003$, $\eta^2p=0.09$) (Figures 71 & 72).

The ART-Anova highlighted a significant effect of vision and plantar stimulation on standard deviation of mediolateral position of CoP (resp. $F(1.59)=15.07$, $p=0.5$, $\eta^2p=0.007$ and $F(2.118)=1.46$, $p=0.23$, $\eta^2p=0.024$) (Figure 73 & 74). Post hoc analysis showed a difference between StimL and the other plantar conditions ($t(118)=-8.71$, $p<0.0001$ for control and $t(118)=-68.69$, $p<0.0001$ for StimR) with the orthotic stimulation on the left being more lateralized.

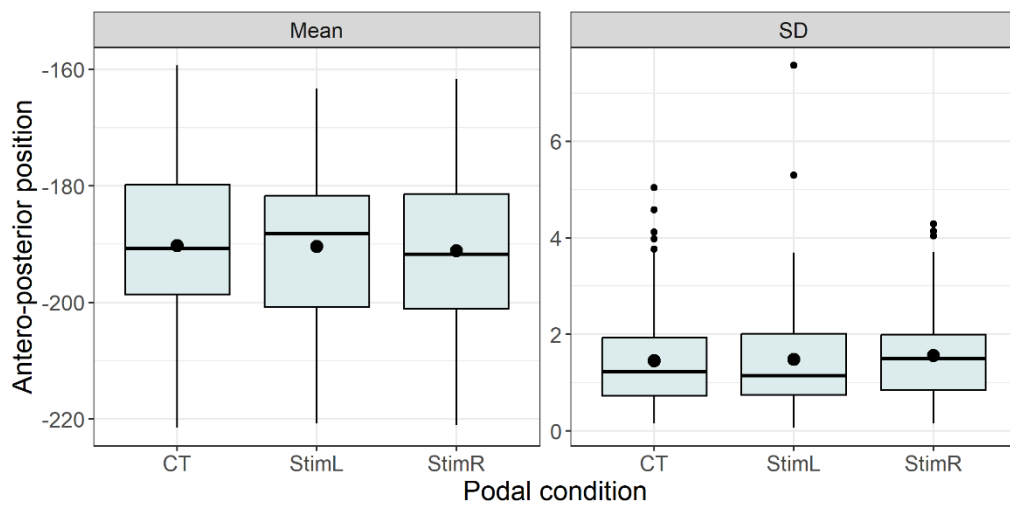


Figure 71: Mean position and standard deviation of CoP on antero-posterior axis

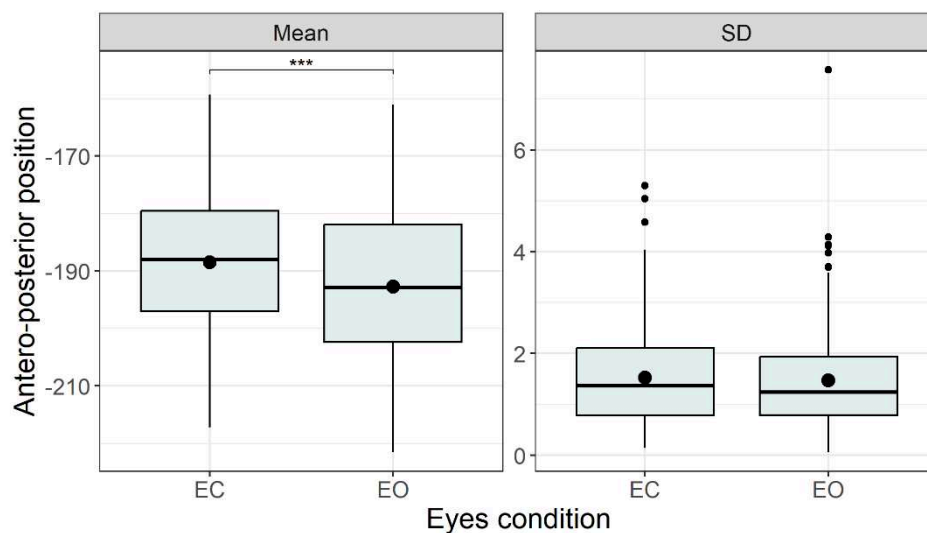


Figure 72: Mean position and standard deviation of CoP on antero-posterior axe under 2 visual conditions

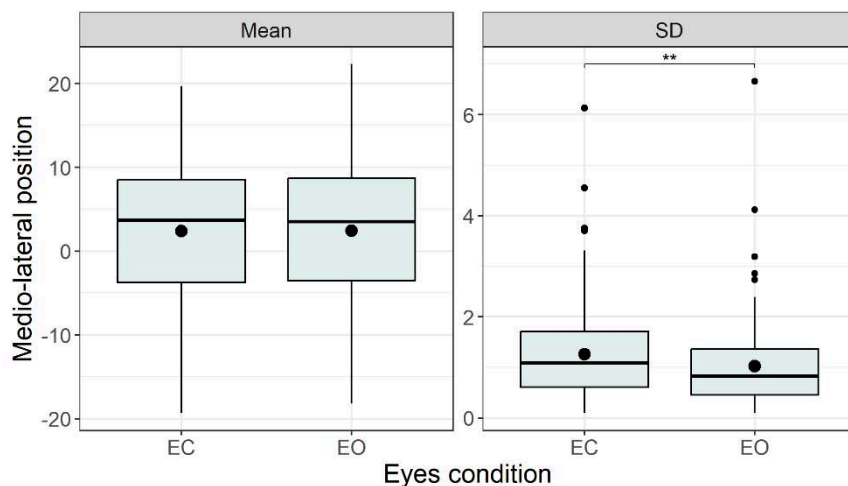


Figure 73: Mean and standard deviation on medio-lateral axe under 2 visual conditions

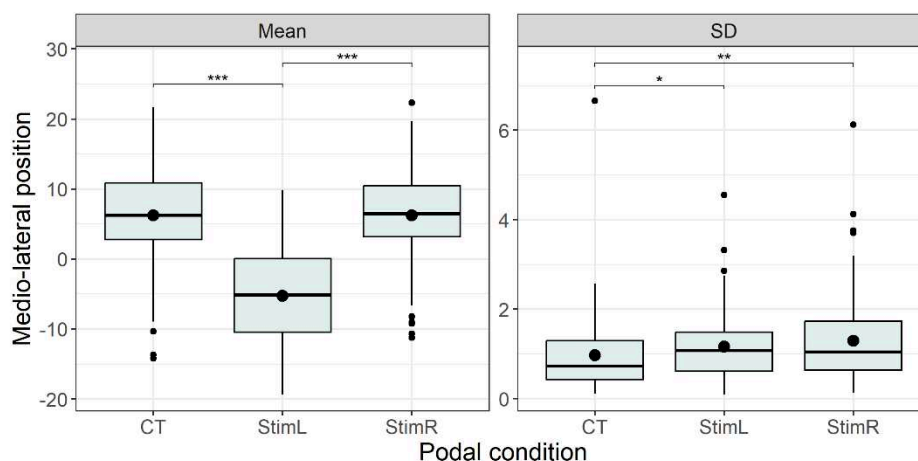


Figure 74: Mean and standard deviation on mediolateral axe under 3 plantar conditions

- **Effect of plantar stimulation and vision on Gait Ratio**

As CoM trajectory is linked to straight or turn condition, this directly impacts the Ratio. We analyzed data by grouping them according to locomotor trajectories.

- Straight trajectory

There was a significant effect plantar stimulation on Gait Ratio as shown on figure 75 ($F(2,76)=20.95$, $p=5.63e^{-08}$, $\eta^2p=0.35$). There was a significant interaction between vision and plantar condition ($F(2,76)=75.12$, $p=2.22e^{-16}$, $\eta^2p=0.66$).

Post hoc analysis showed a significant difference between control and, StimR and StimL (resp. $t(76)=-6.17$, $p<0.001$ and $t(76)=-4.77$, $p<0.001$).

- Turn Left trajectory

There was a significant effect of vision and plantar stimulation on Gait ratio (resp. $F(1.38)=57.58$, $p=3.99e^{-09}$, $\eta^2p=0.60$ and $F(2.76)=6.36$, $p=0.003$, $\eta^2p=0.14$) (Figure 75).

Post hoc analysis showed a significant difference between control and, StimR and StimL (resp. $t(76)=3.028$, $p<0.009$ and $t(76)=3.147$, $p=0.006$).

- Turn Right trajectory

There was a significant effect vision on Gait Ratio as shown on figure 75 ($F(1.38)=19.24$, $p=8.82e^{-05}$, $\eta^2p=0.34$). There was a significant interaction between vision and plantar condition ($F(2.76)=16.58$, $p=1.06e^{-06}$, $\eta^2p=0.30$).

Post hoc analysis showed a significant difference between eyes closed and eyes open ($t(38)=4.39$, $p<0.001$).

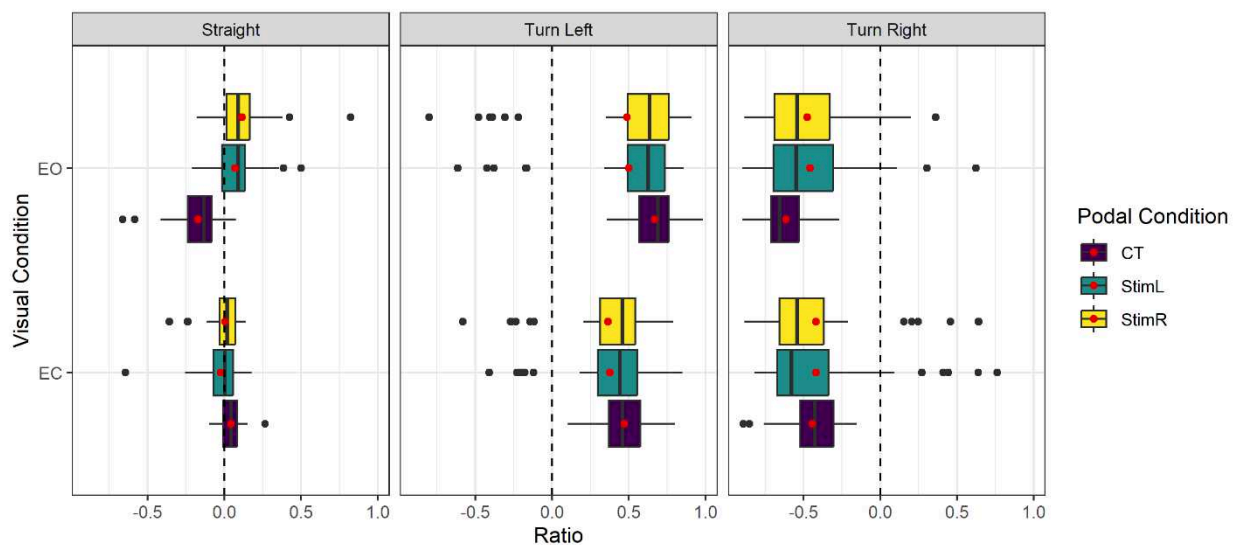


Figure 75: Gait Ratio on 3 trajectories (straight, turn left and turn right) under 2 visual and 3 plantar conditions.

• Correlation between Plantar Quotient and CoP parameters

We highlight a correlation between the PQ (eyes open) and Length of CoP displacement with StimL (eyes open) ($R = 0.262$, $R^2 = 6.84e^{-02}$, $p = 0.0.044$) (Table 12) (Figure 76).

Table 12: Linear correlation values between CoP parameters and PQ

		Linear Regression			
		R	R ²	t	p
StimR	AP position mean	0,182	0,0333	-1,41	0,163
	AP position Standard deviation	0,107	0,0114	0,816	0,418
	ML position mean	0,0536	0,00287	-0,409	0,654
	ML position Standard deviation	0,0961	0,00923	0,735	0,465
	Length	0,24	0,0576	1,88	0,065
	Surface	0,00551	0,0684	0,012	0,573
StimL	AP position mean	0,125	0,0156	-0,959	0,342
	AP position Standard deviation	0,0674	0,00454	0,514	0,609
	ML position mean	0,00609	3,71E-05	0,0464	0,963
	ML position Standard deviation	0,0236	5,56E-04	-0,18	0,858
	Length	0,262	6,84E-02	20,6	0,044 *
	Surface	0,0917	8,40E-03	0,701	0,486

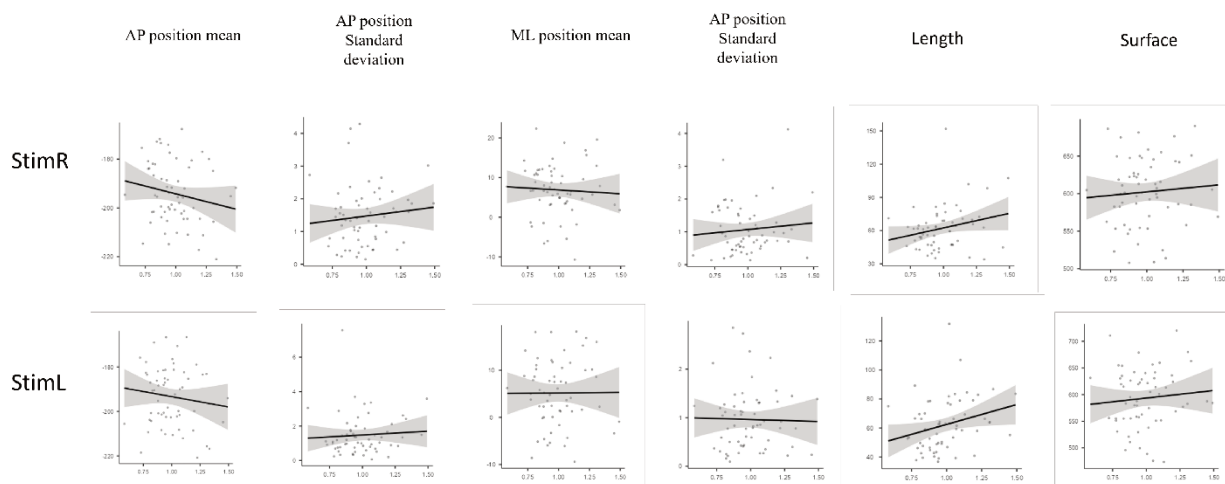


Figure 76: Correlation plots between CoP parameters and QP

- **Correlation between PQ and Gait ratio**

We did not highlight any correlation between the PQ (eyes open) and Gait ratio (eyes open) on the 3 trajectories (Table 13) (Figure 77)

Table 13: Correlation values between PQ and Gait ratio

		Linear Regression			
		R	R ²	t	p
StimR	Straight	0,239	0,0572	-1,5	0,143
	Right Turn	0,592	0,0035	-0,361	0,721
	Left Turn	0,217	0,0472	1,35	0,184
StimL	Straight	0,136	0,0184	-0,832	0,411
	Right Turn	0,201	0,0405	-1,25	0,219
	Left Turn	0,176	3,11E-02	1,09	0,283

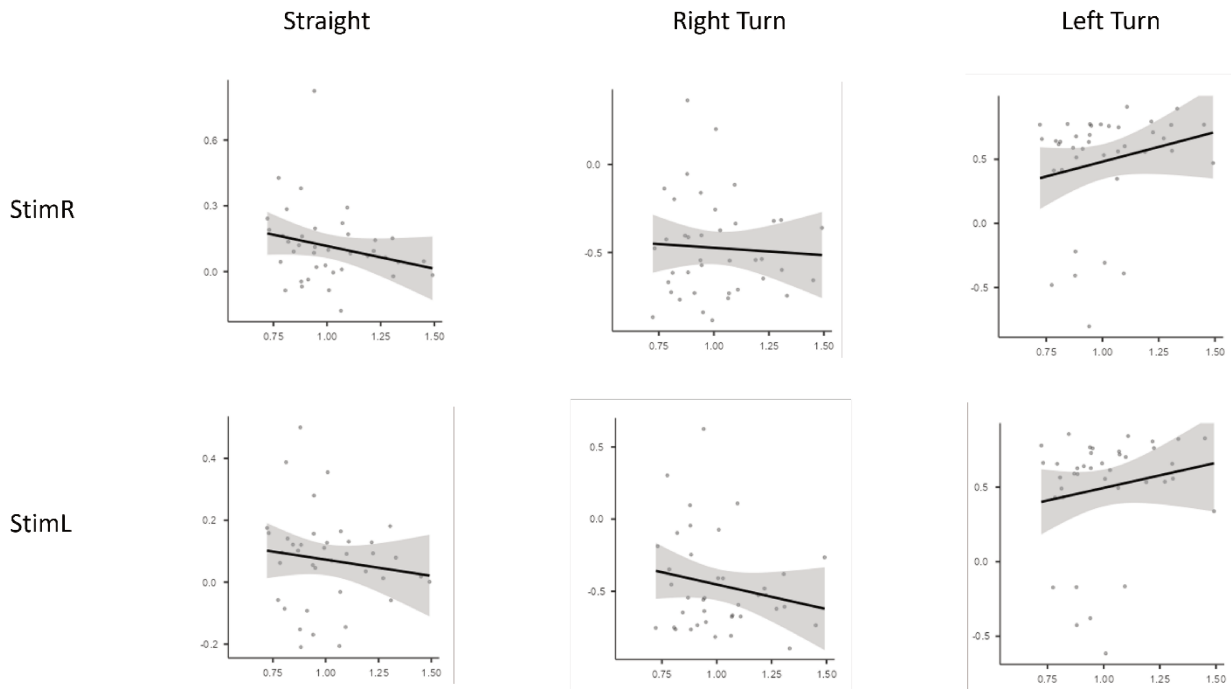


Figure 77: Correlation plots between PQ and Gait ratio

C. Discussion

The objective of this study was to investigate the impact of an orthopedic insole component on both static posture and gait. The medial longitudinal arch support component, previously documented in the literature to induce a lateral shift in the CoP during static standing, was examined (Janin & Dupui, 2009). Bipodal use also demonstrated a modification in the CoP displacement, characterized by an increase in the area of oscillations and the length of displacement of the CoP (Foisy & Kapoula, 2016, 2017; Tramontano et al., 2019).

Our results do not indicate any directed action of the element. Indeed, the hypothesis of lateralization implied a movement of the CoP along the mediolateral axis opposite to the side of stimulation. We did not observe a mirror lateralization when positioning the element under the right foot, followed by placement under the left foot (or vice versa). The provided explanation was that when placing the insole component under one foot, the pressure from mechanoreceptors signals increased support on that side to the system. In response, the static balance induced an opposite reaction to realign the supports and distribute them harmoniously around the CoP.

However, it does induce a disturbance in balance characterized by increased CoP oscillations and greater displacement length. These results are consistent with the existing literature (Foisy & Kapoula, 2017; Tramontano et al., 2019). However, in our case, it is applied unilaterally. Hence, unilateral stimulation appears to be a sufficient sensory signal to challenge static balance. This suggests that a unilateral disturbance is not compensated for by the non-stimulated side. The plantar information is asymmetric during this stimulation. Therefore, the control system integrates unilateral and then bilateral plantar information, resulting in a global and non-directed response.

These findings support the idea of a global integration (Calvert & Thesen, 2004; Sober & Sabes, 2003; Stein & Stanford, 2008).

Nevertheless, this result partially contrasting with the results from the literature, suggests that this element cannot be chosen by the clinician to counteract lateralization. However, it can be speculated that in the case of a deficit in static control, the use of fine stimulation may help regulate posture. New studies are required before clinical implementation in this regard. Postural deficits are indeed related to age and the intrinsic capabilities of individuals (Condon & Cremin, 2014; Ricotti, 2011). Our study population intentionally consisted of healthy adults. It is possible that this element may not induce the same effects in a population with a deficit. The multisensory organization of patients with posture disorders is altered and modified (Liaw et al., 2009).

It's worth noting that the study's results are surprising, particularly regarding the effect of vision. While in all our previous studies and in the literature, the condition with closed eyes increased participants' oscillations, in this current case, the oscillations are less pronounced (both in terms of the CoP surface area and the length of its displacement). Our participants appear to have adopted a different strategy compared to their initial recording in study 1. The previous chapter demonstrated the interaction of the environment with static balance. It is possible that the experimental conditions have influenced the response. Factors such as the participant's clothing and the new environment may have led to enhanced postural control with eyes open (Hainaut et al., 2011). We do not have any additional explanations to account for this difference between open and closed eyes.

If we focus on gait, we also observe an effect of the non-directional orthopedic insole component. The participants' CoM is less laterally deviated when they are stimulated by the orthopedic insole component. Therefore, we have an integration of plantar stimulation, both with eyes closed and open, during the successive footfalls in the walking cycle. Just as in the static condition, the hypothesis of directional response to plantar stimulation is rejected. Indeed, this stimulation reduces the lateralization of the participants compared to the control situation. It can be assumed that this stimulation, by activating the plantar mechanoreceptors, leads to increased control by the subject who realigns their body axis (Le Mouel et al., 2019). The system appears to correct the disturbance as a protective mechanism. This response is physiological and becomes more challenging in the presence of an impairment of balance. It is interesting to note that a 3mm elevation disrupts the locomotor trajectory of healthy subjects. However, is this adaptation subject to learning? The role of orthopedic insoles represents an enhancement of the pathological condition, whether through an improvement in symptoms or underlying causes. This modification induced by the insole element in this study occurs over a short period compared to the duration of orthotic treatment. Tramontano (2019) have shown an amplified effect of the component on the 7th day after its implementation on a static task recording. But the implementation was worn during the time between. Learning seems possible, as the postural response recorded after 7 days shows an improvement in the parameters of the CoP oscillations. However, a later recording also reveals that the level of static balance has returned to a level close to the initial state. This suggests the presence of both learning and plasticity within the system (Stein et al., 2014). The long-term sustainability of the correction remains to be analyzed. Our study population did not exhibit a deficit in static control. Investigating a population with such a deficit would be more relevant to

determine whether an impaired system processes the information provided by the insole in a similar manner and whether this information is maintained and integrated over time.

Our second objective was to ascertain whether the result on the plantar quotient allowed us to observe a specific outcome of insole integration on walking and static posture. As a reminder, we had selected three subpopulations in the first study to ensure that their plantar quotients did not overlap. The calculation of the new plantar quotient does not yield the same distribution of participants. We no longer find three subgroups, but instead, we have a continuous distribution. This quotient does not appear to be stable over time. However, we must clarify that the two studies did not take place during the same time period. It's possible that intrinsic factors of the individual may have influenced their static balance. Since our PQ is a continuous variable, we analyzed the correlations between the parameters of the CoP when plantar stimulation was applied and the PQ. We observed a positive correlation between the PQ result and the CoP displacement length with stimulation under the left foot ($p=0.044$). Let us note that the p-value for the CoP displacement length with stimulation under the right foot is not significant but is close ($p=0.065$). The first point to note is the common variable used: the CoP displacement length. Using the same metric can accentuate a causal relationship because its changes over time follow this common metric. Conversely, while the CoP displacement length may increase, we can sometimes observe that the oscillation area does not evolve in parallel. Furthermore, the correlation indicates an increase in length when applying stimulation under the foot, indicating a challenge to static balance, which is associated with a more pronounced increase in oscillation on the foam pad compared to the control condition. This result, although interesting, is the only one that demonstrates an integration of stimulation and PQ. It's also worth noting that the strength of the regression is weak.

Finally, it's important to note that the laboratory evaluation is not ecologically valid. Conducting the experiment in the laboratory can be more imposing due to the motion capture setup, the specific clothing required, or the presence of the three individuals (often unknown) for data collection. The use of the quotient in a clinical setting appears premature. Environmental and intrinsic factors of healthy subjects seem to influence the responses. Therefore, it is challenging to track individuals over time using this criterion. The issue of temporality is significant, both in terms of integrating the insole component and in patient monitoring. Further research is needed to better understand all the factors that modify the plantar quotient response. Similarly, assessing the plantar integration capacity can be done by reducing information through the use of foam inserts. Based on the results of this study and existing literature, it may be possible to stimulate the system for evaluation purposes. Whether it's a smooth ovoid relief or textured materials, they appear to induce responses in both static and dynamic control. It could be interesting to consider this quotient with a textured material, for example. It is known that the interposition of such materials reduces individual oscillations. Indeed, this nearly constant stimulation activates the motor control system and allows for a continuous alert of the balance system. Considering a "stimulated" rather than "inhibited" PQ could provide new insights into the quality of integration.

Study 5: Visual field and plantar integration

A. Introduction

In this last study, we propose a replication of study 3, considering the population of Study 4. Our objective was to confirm the results of our study 3, in which no correlation link appeared between the participants' plantar arch index and the subjective virtual vertical.

As a reminder, the participants had previously taken part in Study 1. Their selection for Study 4 was based on the PQ criterion. Since the distribution of this parameter was continuous, we divided our initial population of 132 participants (Study 1) into 5 groups and selected groups 1, 3, and 5 to ensure there was no overlap in the PQ data. So, 60 subjects participated in Study 4. Our hypothesis was that our previous results would be confirmed, namely, no correlation between their closed-eye plantar quotient and their visual dependence. The introduction of a foam pad would then not be a challenging source of information for their system, even though we selected 3 different Plantar Quotient groups.

B. Material and method

B.1. Participants

We asked the 60 participants from Study 2 to participate to Study 5. We obtain 52 positive responses. 2 of the participants had a wrong comprehension of the task (abnormal results) and were taken off the analysis.

B.2. Experimental design

The experimental design is similar to Chapter 2 Study 3. The Rod and Frame Test assesses a person's ability to align a tilted visual frame to their perceived vertical while being in a dark room. The experiment was performed with a virtual reality headset. The environment was a black wall in front of the participant with yellow rod and frame. 2 podal conditions were assess: no foam (I.E. control) and foam under feet (Depron®).

Please refer to section Chapter 2 – Study 3 for details.

B.3. Data Analysis

- Dependent variables

In order to determine if the visual field is correlated with the foam pad interposition, we first calculated the Absolute mean error for each trial. The error is the angle (°) between the position of the Rod and the gravitational vertical.

The plantar quotient was computed with Study 4 data, according to the following equation (3) (p.73):

$$PQ = \frac{\text{Length of CoP displacement on foam}}{\text{Length of CoP displacement without foam}} \quad (3)$$

- Statistical analysis

Statistics were performed using Jamovi® and R softwares. Level of significance was set to 0.05. Normality was assessed using the Shapiro-Wilk test. We performed a correlation to evaluate the relationship between the PQ eyes closed obtained in static balance (Study 4) and measures of visual field dependence (RFT). For these simple linear correlations, we examined the sign of the regression equation and R² values were used to determine correlation strength. We also performed a repeated measure Anova between the podal factors (control and foam) on their Absolute mean error.

B.4. Results

- Descriptive statistics

Table 14 presents the Absolute Mean Error at the RFT with or without foam under the feet.

Table 14: RFT descriptive statistics

	Rod and Frame Test	
	Control	Depron®
Mean ± SD	1,32 ± 0.621	1,42 ± 0.982
Median ± IQR	1,30 [0.715]	1,23 [0.982]
IC _{95%}	[1,15 ;1.50]	[1,28 ;1.56]

- Effect of podal condition

Due to non-normal distribution we did a Friedman test to compare the 2 conditions on RFT (control and Depron®). No significant difference was highlighted between the 2 conditions ($p=0.672$).

- Correlation between RFT and Plantar Quotient

We did not highlight any correlations between the PQ eyes closed and RFT ($R = 0.0789$, $R^2 = 0.00623$, $t=-0.549$, $p = 0.586$) (Figure 78).

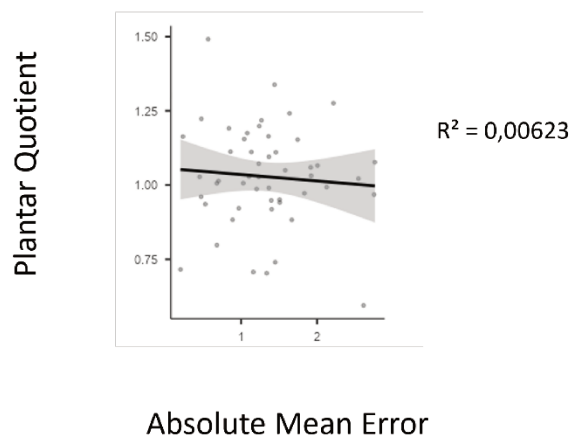


Figure 78: Correlation between plantar quotient from Study 4 and Absolute Mean Error from RFT test

C. Discussion

Just as in Study 3, the results do not show a link between participants' visual dependency and their static balance on a Depron® pad. Given that our study population consists of healthy adults, it appears that multisensory integration compensates for the interposition of foam under the feet. Even in cases of a more pronounced visual dependency, participants' intrinsic capabilities offset the changes brought about by this pad.

In the literature, we do find, however, that in certain pathological populations, visual dependency is correlated with an impairment in their static or dynamic balance (Azulay et al., 2002; Slaboda et al., 2009). Since our study population is healthy, it appears that they have the ability to regulate their static performance when foam pads are interposed, whether their eyes are open or closed. As in the previous study, the use of afferent information is linked to individuals' intrinsic capabilities. Even though some participants show visual dependence in their RFT results, they are not affected by the interposition of foam. The thin foam used in this study does not appear to challenge static balance. However, the interposition of insole elements appears to be associated with visual dependence in subjects with ineffective plantar exteroception (Foisy & Kapoula, 2018). So, it appears that the provision of information is linked to visual dependence, rather than the reduction of plantar information. This result suggests that orthopedic insoles may not be integrated in the

same way based on the results obtained in the RFT and on foam pads. However, we do not find the same subpopulations when subjects are oscillating on thin foam pads.

Finally, studies indicate a correlation between dynamic visual dependence and dynamic balance (Isableu et al., 1998). Further analyses are therefore necessary to better understand in which populations and under what conditions plantar afferents are linked to visual dependence. We would like to emphasize that a more in-depth analysis with additional tests could provide further insights into potential dependencies of individuals.

Chapter 3 Discussion

The objective of this chapter is to analyze the impact of an orthopedic insole on the static and dynamic balance. Orthopedic insoles are designed to provide personalized support to the feet, which can influence an individual's posture and balance. The chosen element is a medial arch support. It has already been analyzed in relation to the static posture of healthy subjects. Positioned under one foot, it induces contralateral lateralization of the CoP with a modification in plantar pressure distribution. However, this study was conducted on a young and gymnastics-expert population on a static task. Both static and dynamic balance can be affected by age and expertise. Other studies have shown a disturbance in static balance with an increase in the CoP area when the element is placed bilaterally. Foisy and colleagues (2017) divided their study population into two subcategories: individuals with efficient plantar exteroception, defined as having a PQ score above 1, and those with inefficient exteroception, characterized by a score below 1. Those 2 populations did not react the same way when they were facing the perturbation. Following the analysis of the plantar quotient in Chapter 1, our objective was to verify whether this quotient is a reliable indicator for assessing the plantar integration of an insole element.

Our results do not demonstrate a directed action of the element, either in static or dynamic conditions. We do not observe a symmetrical reaction when the element is placed on one side and then on the other, both static analysis and during locomotion. However, we do observe a change in the length and surface area of CoP in static conditions. The stimulus imposed by the insole element activates mechanoreceptors and results in a modified static balance. The foam pads tested in the previous chapter did not alter this balance, and visual information took precedence over this input. The relief, and thus the compression of these mechanoreceptors, therefore causes a modification in this multisensory integration. Therefore, we find an effect of the element even with unilateral stimulation. The hierarchy of information appears to be modified, and the external element impacts an effect that is not counteracted by the non-stimulated side.

This provides new insights for the assessment of plantar integrity. It is possible to either inhibit or stimulate the mechanoreceptors. Traditionally, plantar quotients are conducted using foam. Why not stimulating the plantar sole instead of “inhibiting” while evaluating static balance? Textured insoles are materials that are increasingly used in podiatry. They are composed of small raised features called "peaks" that activate mechanoreceptors upon contact. Several studies indicate a modification of static balance as well as gait patterns when wearing these materials (Aruin & Kanekar, 2013; Barbosa et al., 2018; Kenny et al., 2019; Robb & Perry, 2022). In this case, it would be necessary to reevaluate healthy populations and observe the physiological adaptation to this stimulus in order to establish norms for this plantar quotient. However, there are several types of textured insoles found in the literature, and standardization of practices is also necessary in this

regard. Taking into account the results from the literature, this quotient should be below 1, or at the very least, it should be within the physiological range when the ratio is low. The concept of induced laterality by the element was not observed. Podiatrists aim to provide treatment with the goal of correcting lower limb deviations. Being able to attribute a specific action to an element facilitates the logic of treatment creation. Indeed, if a given element produces a known response, it becomes easier to propose a therapeutic solution. Our results do not allow for the definition of a specific action of the element. However, by influencing the movement of the center of pressure, it acts as a protective stimulus with a reduction in this movement. We are aware that the movement of the CoP is coupled with deficits such as the risk of falls in elderly individuals. It reflects the subject's ability to maintain their balance. These types of insole elements can, therefore, be integrated into more comprehensive balance treatments. Their thickness is primarily focused on plantar cutaneous stimulation. However, before proposing this therapeutic solution as a means to improve static balance in individuals at risk of falls, it is necessary to investigate whether their system processes plantar afferents in the same way. Indeed, the intrinsic capabilities of individuals influence the perception and response to these stimuli. In a system with deficits, what will be the role of this element in modifying the individual's static balance? Will the expected outcome be the same, namely an improvement in balance due to a reduction in parameters, or conversely, an increase due to an increase in disturbances not managed by the motor system?

The gait analysis has shown a reduction in the deviation of support in relation to the CoM. Just as in static conditions, we do not find a directional response following the placement of the element. However, while in static conditions it increases oscillation and thus decreases balance, in dynamic conditions, it appears to play a role in reducing variations and stabilizing trajectories. Multisensory integration does not occur in the same way in static and dynamic situations (Mahoney et al., 2019). The prioritization of information is linked to the individual and the task to be performed. In the case of walking, with each step, the foot provides information about the ground, and the subject, being alert, adjusts their walking pattern if they encounter an unstable surface. In a static situation, since the subject does not alter their position, they are initially aware of the ground and, therefore, have less alertness regarding this information. Therefore, the attention given to the stimulus is different, and by extension, the importance assigned to plantar information varies. The induced reaction is not oriented or expected. Through this reduction in lateralization of support in relation to the CoM, the system corrects and re-centers the movement. In static conditions, the stimulation leads to variations in movement, making it more extensive, and the system is disrupted. In contrast, during walking, there is a reduction in this range of movement, and the system, while considering the information, issues a correction signal. This clearly indicates a greater role for plantar information with a more pronounced response to the stimulus. However, the evaluation within a laboratory does not necessarily reflect real-life daily activities. The trajectories were pre-defined, and no obstacles were presented to the participant during their gait. During tasks such as crossing a pedestrian crosswalk, attention is significantly different, with marked visual and auditory information to prevent collision risks (Hahn et al., 2014; Koelewijn et al., 2010). Would this plantar information also be clearly identified under these conditions? The multisensory hierarchy would likely be altered to protect the individual from potential external risks.

Similarly, our analysis was conducted on a healthy population without impairments. It would be interesting to examine the effect of such stimulation on an elderly population or those with balance impairments (Basharat et al., 2019; Hu & Woollacott, 1994; Mahoney et al., 2021). However, the

literature does show significant integration of plantar information in pathological populations, such as individuals with Parkinson's disease or multiple sclerosis. Textured materials have been placed under the feet of these patients, and their gait patterns, which were altered due to their conditions, have been improved (e.g., walking speed, step cadence, etc.) (Lirani-Silva et al., 2017; Nurse et al., 2005; Robb & Perry, 2020). The multisensory integration of these patients is significantly impaired by their pathology, particularly their proprioceptive system. CNS thus prioritizes the received information and selects them based on their reliability. The integration appears to have a lasting effect, and an improvement in the parameters is sustained over time. During a proprioceptive and plantar stimulation, Earhart (2002) demonstrated that the stereotypy of motor trajectories was influenced by this stimulation. However, the healthy subjects were blindfolded, and no additional plantar information was provided between the moment of stimulation and walking (Earhart et al., 2002). As soon as the subjects regained the use of their vision, the locomotor trajectory was readjusted and reliable. The organization of multisensory integration in healthy subjects is more variable, especially during a task without difficulty, such as walking. Individuals have multiple levels of information at their disposal and can control their trajectory. The more the system is impacted by a disease, the more the use of information and its stereotypy is controlled. The assessment of pathological populations is necessary to gain more information on the therapeutic use of these insole elements. We observe an improvement strategy in dynamic balance and an opposite strategy in static balance. Therefore, the task is crucial to investigate in our patients in order to propose the right treatment and to understand how sensory reorganization occurs based on the impairments present and the task asked.

These perspectives are in line with our results regarding visual dependence. It does not appear to impact the plantar sensory integration of our participants. However, pathological populations have shown a link between their visual ability, especially this dependence, and their static and dynamic balance. Since sensory reorganization is altered by a pathological condition, an evaluation of these populations would be more relevant to understand this visual-plantar connection. Similarly, an evaluation of the correlation between orthopedic treatment and visual dependence seems more relevant than the correlation with static balance on foam. Stimulation of mechanoreceptors by the relief on orthopedic insoles appears to elicit a different response than assessing their capacity on a thin foam pad. This result corroborates our static results with insole elements in the sense that plantar system stimulation seems more relevant than a reduction in this information.

All these variations highlight the difficulty in assessing this multisensory integration in a clinical setting. Intra-individual characteristics further increase the complexity of the task. The challenge for the practitioner is to validate their treatment and be able to answer the question: is the proposed treatment the right one? In our work, we observed changes in postural oscillations and walking patterns following the placement of insoles. These data provide us with real insights into the level of interpretation and prioritization of plantar information during these tasks, rather than the timing and choice of application of these stimulations. However, the standardization of measurements in order to compare our data can obscure the real-world context of the task at hand. In other pathologies, ecological evaluation has demonstrated its added value by providing a more accurate assessment of the patient's condition (Farias et al., 2003; Stellmann et al., 2015). A clinical evaluation closer to the patient would allow for the visualization of the potential effects of insoles

during daily activities in a more neutral environment than the highly controlled setting. This would bring the sensory weighting closer to reality and lead to more suitable therapeutic choices. Static and dynamic balance should be evaluated in addition to a multidisciplinary approach which is also necessary to consider all potential deficits in the individual and improve their overall condition by addressing multiple systems if necessary.

Conclusion

The aim of this work was to standardize and evaluate clinical practices in podiatry. Our results demonstrate a significant impact of the measurement context. This initial point is particularly important. In fact, the lack of standardization in measurement locations leads to different responses from the same patient. Consequently, it becomes impossible to compare these results among professionals. There is a need for the standardization of measurement protocols as well as the parameters chosen for evaluation. Standardization within our own clinical practice will enable us to compare the patient over time. This will help minimize biased results. Particular attention should be paid to the visual information provided to the patient. Indeed, our results show a strong impact of this information, indicating a potential bias in evaluations if the information provided is not standardized. The thin foam pads do not seem to pose a challenge for our participants. However, some participants have exhibited results that fall outside the norm. A specific analysis of these exceptional cases would likely help to better understand potential clinical outcomes. These participants have easily integrated into the study and are considered healthy. Nevertheless, their atypical results compared to the rest of the group could provide a better understanding of sensory interactions and reweighting.

The use of the PQ should be measured and combined with other tests to highlight any potential plantar integration deficit. We do not find a link between this quotient and the integration of insole components. These results differ from the literature and require further research to explain them. The stimulation of mechanoreceptors appears to induce a modification in static and dynamic balance. It is therefore wise to question the evaluation by the PQ as it is. If the stimulation induces a response and one seeks to assess the ability to integrate plantar information, it may be more relevant to calculate the PQ ratio between a stimulation situation and a control situation.

Although challenging in clinical routine, the analysis of locomotor trajectory appears to be valuable in assessing the sensory integration of orthopedic insoles. Adjustments in practices and materials, may need to be considered. This would provide professionals with a new evaluation tool. A combined analysis of static and dynamic results is necessary to be ecological and more relevant.

Validation work on populations with deficits should also be conducted. Sensory weighting is closely related to the subjects' abilities and the tasks required. Fragmented evaluations, as often seen in the literature, provide clues about the capabilities of pathological subjects. A comprehensive assessment of these patients, both in static and dynamic contexts, as well as their therapeutic plan, would help evaluate the impact of modifying plantar information through orthopedic insoles. These findings should be integrated into an evidence-based practice, taking into account both patient considerations and clinical data.

This work contributes to the knowledge in the field of podiatry not only clinical tests but also the treatments that are offered by the podiatrist. Further research is needed to deepen our understanding. However literature frequently exhibits divergent findings with respect to the effectiveness of orthopedic insoles in clinical care. This variance in research outcomes can be attributed to the difficulty in comparing studies. Moreover, it should be noted that the profession of podiatry is subject to variations and distinctions across different countries. Thus, there is a strong need for standardization and alignment of clinical practices and knowledge within this field, which would greatly benefit the profession as a whole. A concrete illustration of the necessity for this standardization is the limited adoption of textured materials in orthopedic insoles within the French healthcare landscape. Despite this, it is important to acknowledge that research has demonstrated promising and beneficial outcomes in the context of gait analysis, both in healthy individuals and those with pathological conditions. Therefore, a stronger link must be established between research and clinical practice to facilitate the seamless transfer of data and knowledge.

Finally, the tests conducted, and research should aim for ecological validity. They should, to the greatest extent possible, reflect daily reality. This dimension seems essential for the optimal care of patients. Assessing a non-ecological situation and basing therapeutic decisions on it can certainly lead to clinical applications that are not well-suited. In this regard, gait analysis in podiatry clinics appears essential. Instrumented analysis provides more precise data. However, the laboratory tools used in this study are not easily transferable to the clinical setting. The dissemination of clinical tools for such evaluations would be a valuable addition for professionals, allowing them to enhance their analysis and cross-reference more information effectively. Hence, a continued connection between podiatry and research, especially with motion analysis laboratories, is essential. These collaborations can provide the tools and knowledge needed to advance both the understanding and practices in the field.

The need to develop this connection with research in France is clear. Few professionals pursue this path due to the limitations of the clinical practice-oriented qualifications they hold. Nevertheless, there is a significant demand for research in various aspects of the podiatry profession. This demand is driven by the lack of validity in some of the tests used, an incomplete understanding of pathological mechanisms, and the mechanisms of action of orthopedic insoles. These factors present challenges in providing effective care and treatment. Currently, only a small group, comprising less than twenty professionals, has made the decision to further their careers by engaging in clinical research within the field of podiatry. Hence, there is a need for a shift in the educational landscape to make this career choice more accessible and to enable more individuals to choose the path of clinical research. Additionally, there should be a stronger integration of research within the educational curricula, ensuring that professionals are equipped with the necessary skills to read and analyze scientific information. This would empower them to deliver evidence-based practice and contribute to the advancement of the field. Taking inspiration from countries where podiatry is already research-oriented, one potential solution is to establish research units within podiatry institutes, closely linked to the scientific community within the region, such as universities. This approach can lead to several possibilities for collaboration in various fields, including movement science, medical science, rehabilitation science, cognitive science or social and human sciences. The care of individuals raises broad and interdisciplinary questions, whether they pertain to the technical aspects of treatment, measurement tools, or patient care. Indeed, there is a significant need for evolution in the field to ensure that the new generation of podiatrists is

equipped to address these complex questions and challenges. This evolution should include a stronger emphasis on research, interdisciplinary collaboration, and the integration of scientific knowledge into podiatry education and practice. This way, the profession can advance and provide more effective care to patients.

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Normalisation et évaluation des pratiques cliniques en podologie :

Contrôle postural et locomotion

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Introduction

Le pied est une structure complexe composée de 26 os, de 32 muscles et de plus de 20 tendons, le tout organisé en 33 articulations. Autour de ce système complexe se trouve la peau, qui joue un rôle essentiel en protégeant les structures sous-jacentes et en transmettant des informations sensorielles au système nerveux central (Drake et al., 2005).

Le pied est le sujet d'étude et d'intervention des podologues. La podologie est une spécialité paramédicale en France qui se concentre sur le diagnostic, le traitement et la prévention des problèmes liés aux pieds, aux chevilles et aux membres inférieurs. Les podologues sont compétents dans la gestion des troubles musculo-squelettiques pouvant affecter la posture, l'équilibre et la locomotion. Leur expertise, réglementée par plusieurs lois en France (Loi 2023-379, loi 2020-475, loi 2019-774, article 27 de la loi 2009-956) (Journal officiel, s.d.), réside donc dans l'évaluation de ces fonctions grâce à l'analyse plantaire (Bonanno et al., 2017; Spink et al., 2011). De plus, ils sont bien équipés pour traiter diverses affections liées aux pieds telles que la douleur, les blessures, les déformations et les infections. Les podologues peuvent également fournir des dispositifs orthopédiques, prescrire des médicaments et donner des conseils sur les soins des pieds appropriés et les chaussures adaptées. Grâce à leur expertise, ils contribuent à améliorer la mobilité du patient, ont un impact significatif sur la santé musculo-squelettique globale et la posture, et sur la qualité de vie en général. La collaboration avec d'autres professionnels de la santé, tels que les kinésithérapeutes et les spécialistes orthopédiques, peut encore améliorer les soins complets prodigués aux patients atteints de troubles musculo-squelettiques complexes (Loi 2023-379, loi 2020-475, loi 2019-774, article 27 de la loi 2009-956) (Journal officiel, s.d.).

L'évaluation est donc un aspect fondamental des tâches des podologues. Plusieurs outils et évaluations sont classiquement utilisés (Barnett, 1998; Barnett-Cowan & Harris, 2009; Barton et al., 2009; Harrison-Blount et al., 2019; Liebermann & Katz, 2003; Martin & McPoil, 2005; Redmond et al., 2008):

- Antécédents du patient
- Examen physique
- Évaluation de la chaussure
- Amplitude de mouvement
- Force et flexibilité musculaires
- Évaluation de la posture du pied
- Cinématique de la marche
- Évaluation de l'équilibre statique

La fonction sensorielle du pied est bien documentée en tant que rôle informatif (Tresilian, 2012). Collectivement, les informations transmises par les pieds au cerveau contribuent à la proprioception générale et à la prise de conscience du corps. Une bonne communication entre les

pieds et le système nerveux central est cruciale pour une démarche équilibrée, une posture appropriée et une coordination harmonieuse des mouvements. Par conséquent, le rôle informatif du pied est d'une importance cruciale dans notre vie quotidienne et nos activités physiques (Shumway-Cook & Woollacott, 2007). Il existe plusieurs moyens d'évaluer la capacité sensorielle du pied. Les tests sensoriels sont couramment utilisés par les professionnels de la santé tels que les podologues, les neurologues et les kinésithérapeutes pour évaluer la sensibilité tactile et proprioceptive du pied.

Un des outils cliniquement utilisés est le coussin en mousse pour évaluer le contrôle de l'équilibre du patient. Le coussin en mousse est constitué d'une surface instable et rembourrée conçue pour créer un environnement instable sous les pieds et mettre au défi le contrôle de l'équilibre du patient. Cela évalue la capacité à maintenir l'équilibre dans des conditions statiques et est analysé à l'aide d'une plateforme de force en enregistrant les mouvements du centre de pression (CoP) (Patel et al., 2008). Cette évaluation est particulièrement utile pour identifier d'éventuels problèmes d'équilibre ou des déficits proprioceptifs qui peuvent être liés à la capacité sensorielle du pied.

L'équilibre statique fait référence à la capacité de maintenir la stabilité et le contrôle lors d'une position stationnaire, comme debout (Shumway-Cook & Woollacott, 2007). En revanche, l'équilibre dynamique est la capacité de maintenir la stabilité et le contrôle pendant le mouvement ou la locomotion, comme la marche, la course ou le saut. (Rosenbaum, 2009). Contrairement à l'équilibre statique, l'équilibre dynamique nécessite des ajustements continus en réponse à des conditions changeantes, telles que des changements dans la répartition du poids et des variations du terrain. Le lien entre l'équilibre statique et l'équilibre dynamique réside dans leur interdépendance. L'équilibre statique fournit la base de l'équilibre dynamique. Un alignement et un contrôle appropriés en position statique sont essentiels pour initier et maintenir des mouvements contrôlés pendant la locomotion. Lors de la marche, le centre de masse du corps se déplace continuellement et passe d'un pied à l'autre. Cela nécessite un bon équilibre statique pour exécuter des mouvements fluides et coordonnés sans compromettre la stabilité (Lajoie et al., 1993). Les informations sensorielles utilisées pour l'équilibre statique sont cruciales pendant la locomotion, où elles informent continuellement le cerveau de la position du corps, de ses mouvements et de son interaction avec l'environnement. Comme l'équilibre statique et l'équilibre dynamique sont des composants complémentaires du contrôle postural, le déficit de l'un peut influencer l'efficacité de l'autre, et les deux sont essentiels pour maintenir la stabilité et une locomotion efficace. Pour acquérir une compréhension globale de l'intégration sensorielle podale pendant la locomotion, il est essentiel d'incorporer l'analyse de la marche, qui peut fournir des informations plus précises sur l'interaction du pied avec le sol, la répartition du poids et les réponses proprioceptives pendant la marche (Robb & Perry, 2022). Bien que les tâches statiques puissent fournir des informations utiles sur l'équilibre statique et l'intégration sensorielle, elles ne représentent peut-être pas entièrement l'intégration sensorielle podale dynamique d'une personne pendant la locomotion. Il convient donc de prendre en considération à la fois les tâches statiques et dynamiques lors de l'évaluation de la fonction du pied. En combinant les évaluations statiques et dynamiques, les professionnels de la santé peuvent obtenir une vue plus complète de l'intégration sensorielle podale d'une personne et de son impact sur l'équilibre et la stabilité lors de différentes activités. Cela permet d'identifier d'éventuels déséquilibres dynamiques ou des problèmes spécifiques à la locomotion et de permettre des interventions plus personnalisées et ciblées, notamment sur les dispositifs orthopédiques.

À mesure que notre compréhension des soins de santé progresse, l'importance de la pratique basée sur des preuves devient une priorité. Il est essentiel d'adopter une approche basée sur des preuves pour les soins, ce qui implique l'utilisation des dernières publications scientifiques, des préférences du patient et de l'expertise du clinicien pour fournir les meilleures solutions possibles. En intégrant des informations scientifiques à jour dans les processus de diagnostic et de traitement, les professionnels de la santé peuvent s'assurer que leurs décisions sont bien informées et reposent sur les connaissances les plus récentes disponibles. Cette approche améliore non seulement la qualité des soins, mais favorise également un traitement centré sur le patient.

Cette thèse est profondément ancrée dans ses applications cliniques. Les objectifs de cette recherche sont de mieux comprendre l'évaluation de l'intégration plantaire et de fournir des lignes directrices pour les cliniciens afin d'effectuer une telle évaluation. Cette thèse s'intéresse particulièrement aux évaluations utilisant des coussins en mousse. Le premier chapitre présente la littérature liée aux sujets abordés dans ce travail. Le deuxième chapitre vise à évaluer l'impact de l'information plantaire lors d'une tâche statique. Comme il n'existe pas d'évaluation standard en ce qui concerne sa fonction, il est nécessaire de comprendre et de normaliser l'impact de l'information visio-podale. Le troisième chapitre vise à évaluer l'intervention du podologue en statique et en dynamique, avec l'exemple d'une semelle orthopédique.

Chapitre 1: Etat de l'art

A. Contrôle moteur et Equilibre

Le contrôle moteur englobe des processus et mécanismes complexes pour planifier, exécuter et coordonner les mouvements. Ces mouvements peuvent aller des actions simples telles que la marche à des activités complexes comme jouer de la batterie ou faire de la gymnastique. Le contrôle moteur implique divers composants sensoriels, neuronaux et musculaires travaillant ensemble pour réaliser des mouvements précis et intentionnés. Il englobe à la fois des contributions centrales (SNC) et périphériques (muscles, nerfs et récepteurs). Le SNC génère des commandes motrices, tandis que les composants périphériques exécutent ces commandes par le biais de contractions musculaires (Rosenbaum, 2009).

Plusieurs théories de contrôle moteur ont été proposées pour expliquer comment le système nerveux central (SNC) planifie, exécute et coordonne les mouvements. Ces théories ont été examinées par Shumway Cook (Shumway-Cook & Woollacott, 2007) et nous aident à comprendre les mécanismes sous-jacents et les processus impliqués dans le comportement moteur humain. Ces théories offrent différentes perspectives sur la manière dont le système nerveux central contrôle le mouvement, et bon nombre d'entre elles ne sont pas mutuellement exclusives. L'une des clés d'un mouvement efficace est la stabilité. En effet, le contrôle moteur et le contrôle de l'équilibre sont fondamentalement enracinés dans la relation complexe entre le mouvement et la stabilité. Le contrôle de l'équilibre est un aspect spécialisé du contrôle moteur qui se concentre sur le maintien de l'équilibre et de la stabilité lors de diverses activités (Winter et al., 1990). Ces deux concepts sont étroitement liés, tant en statique qu'en dynamique. D'une part, l'équilibre est un état dans lequel les forces et les couples se compensent, ce qui se traduit par aucune accélération nette. La stabilité, d'autre part, est une mesure de la capacité d'un objet ou d'un système à revenir à l'équilibre après avoir été perturbé.

Tout comme le contrôle moteur, le contrôle de l'équilibre repose sur l'apport sensoriel du système vestibulaire, du système visuel et du système somatosensoriel.. Ils fournissent des informations sur la posture du corps, le mouvement et l'environnement. Ces informations sont utilisées pour générer des commandes motrices permettant le mouvement (Nashner, 1982). L'intégration de l'entrée sensorielle utilise les informations du système vestibulaire dans l'oreille interne en détectant les changements de position et de mouvement de la tête (Peterka, 2018). Le système visuel fournit des informations sur l'orientation du corps et la localisation des menaces potentielles par rapport aux repères de l'environnement externe. Le système somatosensoriel comprend des récepteurs dans la peau, les muscles, les tendons et les articulations. Il fournit des informations sur la position du corps, les mouvements et les forces agissant sur le corps. Les informations de ces systèmes sensoriels sont transmises au cerveau via des voies neurales dédiées. Les informations vestibulaires voyagent à travers le nerf vestibulocochléaire, les informations visuelles à travers le nerf optique, et les informations somatosensorielles à travers divers nerfs associés à différentes parties du corps. Le système nerveux central traite les informations sensorielles entrantes dans des zones spécialisées, telles que des régions cérébrales spécifiques (cervelet, noyaux du tronc cérébral et le cortex somatosensoriel). En intégrant ces informations provenant de différentes sources, le

système nerveux central crée une image réaliste du mouvement et de la position du corps dans l'environnement environnant. Le système nerveux central a la capacité d'apprendre de l'expérience et est capable de comparer l'entrée sensorielle au modèle de référence antérieur de l'équilibre (Shumway-Cook & Woollacott, 2007; Tresilian, 2012). Il s'agit d'une manière plus efficace de réagir et d'anticiper les défis liés à l'équilibre grâce à des stratégies apprises. Cela s'appelle la plasticité du système nerveux central. Ce processus d'apprentissage implique le renforcement des voies neurales et l'optimisation des commandes motrices (Surgent et al., 2019; Winter et al., 1990). Sur la base des informations sensorielles intégrées et de la comparaison avec le modèle de référence interne, le système nerveux central génère des commandes motrices pour activer les muscles et effectuer des ajustements d'équilibre. À mesure que les muscles répondent aux commandes motrices et effectuent des ajustements, des rétroactions sensorielles sont générées (Dietz, 2002). Cette rétroaction fournit des informations sur l'efficacité des contractions musculaires pour maintenir l'équilibre. Le système nerveux central surveille en permanence cette rétroaction et peut ajuster les commandes motrices en temps réel pour assurer la stabilité. Le traitement neural pour le contrôle de l'équilibre est hautement adaptatif. Le système nerveux central affine en permanence les commandes motrices en fonction des modifications de l'entrée sensorielle et de la rétroaction. Par exemple, lorsque l'on se tient sur une surface instable, le système nerveux central peut augmenter l'activité musculaire et la tension pour contrer l'instabilité. Les mêmes mécanismes neuronaux qui coordonnent l'activation musculaire pour les mouvements sont sollicités pour stabiliser le corps lors de défis d'équilibre, avec des ajustements minimes constamment en cours pour contrer les perturbations et maintenir la stabilité. Les muscles, en particulier ceux des jambes et du tronc, jouent un rôle crucial dans le contrôle de l'équilibre (Laughton et al., 2003). Le traitement neuronal dans le contrôle de l'équilibre implique la communication et l'intégration complexes des informations sensorielles, des voies neurales et des commandes motrices au sein du système nerveux central. Cette communication et ce processus sont appelés intégration multisensorielle (Barnett-Cowan & Harris, 2009; Bronstein, 2016). Il s'agit d'un processus neurologique et cognitif grâce auquel les informations provenant de différentes modalités sensorielles sont combinées et traitées pour former une perception ou une représentation unifiée du monde extérieur. Cette intégration permet aux individus de percevoir et d'interagir avec leur environnement de manière plus complète et précise. Comme elle implique la capacité du cerveau à fusionner et à combiner des informations provenant de différentes sources sensorielles, cette intégration aboutit à une perception améliorée et à un meilleur traitement sensoriel par rapport à une seule modalité sensorielle. Cela peut conduire à des jugements plus précis et à des temps de réaction plus rapides. Pour mieux comprendre l'impact de l'environnement sur l'équilibre statique et dynamique, il est nécessaire de connaître les différents systèmes d'afférences et leur rôle dans ces tâches. Dans une tâche statique, ils contribuent indirectement en influençant l'entrée globale du système vestibulaire, qui est intégrée avec des repères visuels et proprioceptifs pour assurer la stabilité et une orientation adéquate. Lors de la locomotion, ils jouent un rôle crucial en aidant à maintenir l'équilibre et à stabiliser la vision en détectant les mouvements de rotation de la tête résultant du balancement naturel du corps à chaque pas. Ces mouvements incluent des changements subtils de tangage, de roulis et de lacet à mesure que le poids du corps se déplace. Ils aident le système nerveux central à anticiper et à s'ajuster à ces mouvements (Lindeman, 2013).

A. Equilibre statique

1.1. Définitions et mécanismes

L'équilibre statique est la capacité d'un individu à maintenir une posture verticale et stable lorsqu'il est immobile. Le maintien de l'équilibre statique est un processus complexe qui implique l'intégration d'informations sensorielles, le contrôle moteur et des ajustements biomécaniques (Alexander & Kinney LaPier, 1998; Shumway-Cook & Woollacott, 2007; Tresilian, 2012) .

Atteindre la stabilité dans l'équilibre statique implique de maintenir le centre de masse du corps au-dessus de sa base de support, de minimiser les oscillations ou les inclinaisons, et de prévenir les chutes. Le concept d'équilibre est essentiel pour comprendre comment le corps maintient la stabilité. Pour atteindre l'équilibre, le centre de masse du corps (CoM) doit être positionné au-dessus de sa base de support (BoS) (Tresilian, 2012; Winter et al., 1990). L'équilibre fait référence à un état dans lequel un objet ou un système est soumis à des forces équilibrées, ce qui le maintient stationnaire ou en mouvement avec une vitesse constante (sans accélération). La stabilité, en revanche, est liée à la manière dont un objet ou un système réagit aux perturbations ou aux petites déviations de sa position d'équilibre.

Le centre de masse (CoM) est le point théorique où sa masse est répartie de manière égale. Il s'agit de l'emplacement moyen de la masse du corps. Pour calculer le CoM, le corps est divisé en segments (tête, bras, jambes, tronc), et le CoM de chaque segment est estimé en se basant sur des repères anatomiques et les masses connues des segments d'après des tables anthropométriques (Winter, 2009). Ces CoMs segmentaires sont ensuite combinés pour estimer le CoM de l'ensemble du corps. Il est utilisé pour simplifier le système corporel en un seul point (Clauser et al., 1969). La base de support (BoS) fait référence à la zone sur laquelle un objet ou une personne est en contact avec la surface de support, comme le sol. Elle peut varier en taille et en forme. En posture debout, elle inclut généralement la zone couverte par les deux pieds lorsqu'ils sont en contact avec le sol. La forme peut changer si les pieds sont rapprochés ou écartés, ou si l'un des pieds est levé. Lorsque la base de support est plus large, la projection du centre de masse a plus d'espace pour se déplacer à l'intérieur sans faire basculer le corps (Latash et al., 2010). L'équilibre n'est pas un état fixe mais plutôt un processus dynamique impliquant des ajustements continus. Pour effectuer ces ajustements, le corps s'appuie constamment sur une boucle de rétroaction sensorielle concernant son orientation dans l'espace et effectue des mouvements réflexes et volontaires pour contrer les écarts par rapport à une posture stable. Plusieurs stratégies ont été proposées pour expliquer comment le corps maintient la stabilité en position stationnaire . La stratégie de la cheville met l'accent sur les contributions de l'articulation de la cheville et des muscles qui l'entourent. Elle suggère que le corps utilise principalement des ajustements au niveau de l'articulation de la cheville pour maintenir la stabilité. Les muscles des jambes inférieures sont activés pour contrôler les petites perturbations et les déplacements du poids corporel. La stratégie de la hanche est similaire à la stratégie de la cheville. Dans des situations où la stratégie de la cheville peut ne pas être suffisante, le corps engage des muscles plus importants autour des hanches pour stabiliser le corps. La stratégie de "changement de base de support" repose sur le concept que le corps ajuste sa base de support pour maintenir l'équilibre. En modifiant la position des pieds ou d'autres parties du

corps, le corps peut se stabiliser (Runge et al., 1999). Le modèle d'intégration sensorielle met l'accent sur le rôle de l'information sensorielle provenant des systèmes d'afférences.

Pour décrire ces stratégies, le modèle du "pendule inversé" simplifie la représentation du corps humain. Le concept de ce pendule est étroitement lié à la théorie de l'équilibre et de l'équilibre, en particulier dans le contexte de la posture et de la locomotion humaine (Loram & Lakie, 2002). Le modèle du pendule inversé est souvent utilisé pour décrire la mécanique de la manière dont les humains maintiennent leur équilibre lors de la marche et d'autres formes de mouvement dynamique (Milton et al., 2009).

Dans ce modèle, le corps humain est comparé à un pendule inversé, où le centre de masse du corps est situé au-dessus du point de contact avec le sol. Ce modèle simplifie la mécanique du corps pour analyser l'équilibre et la démarche. L'analyse du mouvement du centre de masse décrit le mouvement continu du pendule (Gage et al., 2004).

1.2.Évaluation de l'équilibre statique

L'évaluation de l'équilibre statique implique souvent l'utilisation d'une plate-forme de force. Cet appareil est utilisé pour mesurer les forces et les couples exercés sur lui par une personne en position debout (ou effectuant d'autres activités statiques). Il fournit des données sur la répartition du poids d'un individu, le mouvement du centre de pression (CoP). Le CoP fait référence au point sur une plate-forme de force où la force résultante des forces de réaction verticales du sol est appliquée. En surveillant le mouvement du CoP, les chercheurs et les cliniciens peuvent analyser l'équilibre et le contrôle postural d'un individu. La trajectoire du CoP permet de comprendre comment la répartition du poids change et comment un individu s'ajuste pour maintenir la stabilité. Un CoP stable indique que la répartition du poids de l'individu est centrée sur la BoS. Si le CoP se déplace à l'extérieur, cela suggère un changement de poids et des défis potentiels en matière d'équilibre. Le mouvement du CoP au fil du temps est appelé oscillation posturale. L'oscillation posturale implique des oscillations à la fois en amplitude (combien le corps bouge) et en fréquence (à quelle vitesse il bouge). Ces oscillations sont généralement très petites et se produisent à une fréquence d'environ 0,1 à 2 Hz. Elles ont tendance à augmenter avec l'âge, ainsi que chez les personnes ayant des troubles de l'équilibre ou certaines affections médicales (Abrahamová & Hlavačka, 2008; Teasdale et al., 1991). Une oscillation posturale excessive ou irrégulière peut indiquer des déficits en matière d'équilibre (Massion, 1994; Newell et al., 1993; Ruhe et al., 2010).

Divers paramètres sont mesurés et quantifiés pour caractériser l'étendue, la fréquence, la direction et les modèles du mouvement du CoP pendant la station debout statique. L'amplitude de l'oscillation fait référence à la distance parcourue par le CoP par rapport à sa position moyenne ou de référence. Elle reflète l'ampleur des mouvements de balancement du corps d'avant en arrière ou de gauche à droite (Błaszczyk et al., 2011). Des amplitudes d'oscillation plus importantes peuvent indiquer une stabilité réduite. La surface d'oscillation représente la zone couverte par la trajectoire du CoP sur la plateforme de force. Une plus grande surface d'oscillation indique un mouvement global plus important. La vitesse d'oscillation mesure à quelle vitesse le CoP se déplace. Elle quantifie la vitesse des oscillations de balancement postural (Yamamoto et al., 2015). Des vitesses d'oscillation plus élevées peuvent suggérer des difficultés à contrôler l'équilibre. Étant donné que le temps d'enregistrement est standardisé, la vitesse d'oscillation est directement liée à la longueur

du déplacement du CoP. La fréquence d'oscillation indique combien d'oscillations se produisent dans un laps de temps spécifique. Elle est mesurée en hertz (Hz). Les fréquences dans la plage de 0,1 à 2 Hz sont courantes dans l'analyse de l'oscillation posturale. Des paramètres tels que l'amplitude moyenne de l'oscillation, l'écart-type, la racine carrée de la moyenne, et l'étendue fournissent des résumés statistiques des données d'oscillation, aidant à décrire la variabilité et l'ampleur de l'oscillation posturale (Kim et al., 2010; Palmieri et al., 2002). L'oscillation posturale peut se produire dans différentes directions (avant-arrière, latérale). La quantification de l'oscillation dans des directions spécifiques peut fournir des informations sur les directions qui pourraient être plus difficiles pour un individu. Certaines analyses impliquent la décomposition des données d'oscillation posturale en composantes de fréquence à l'aide de méthodes telles que l'analyse de Fourier ou les transformées en ondelettes (Sezer & Ferdjallah, 2005). Cela peut aider à identifier les fréquences dominantes et les modèles d'oscillation. Les mesures de complexité, telles que l'entropie d'échantillonnage ou l'entropie approximative, évaluent l'irrégularité des données d'oscillation posturale (Ramdani et al., 2009). Ces mesures offrent des informations sur les stratégies de contrôle du corps. Les paramètres d'oscillation posturale peuvent être comparés entre les individus ou les groupes pour identifier les différences liées à l'âge, aux conditions de santé, aux interventions ou à d'autres facteurs. (Vuillerme et al., 2008). Les chercheurs et les cliniciens comparent souvent les paramètres d'oscillation posturale entre différentes conditions (par exemple, yeux ouverts par rapport à yeux fermés, surface stable par rapport à surface instable) pour comprendre comment les facteurs influencent le contrôle de l'équilibre (Shumway-Cook & Horak, 1986).

Pour minimiser la variabilité individuelle, il est recommandé de faire des tests de reproductibilité dans la même condition. Il semble nécessaire de réaliser de 3 à 5 répétitions pour obtenir des données fiables pour l'ensemble des paramètres lors d'un essai de 30 secondes, et 2 répétitions pour un essai de 120 secondes. Il a été démontré que la longueur et la vitesse du mouvement du CoP sont plus reproductibles que sa zone, lors de comparaisons (Ruhe et al., 2010; Salavati et al., 2009).

B. Equilibre dynamique: illustration de la marche

1.1.Définitions et mécanismes

L'équilibre dynamique fait référence à la capacité d'un individu à maintenir la stabilité et le contrôle de son corps en mouvement ou lorsqu'il est soumis à des forces externes. Lorsque vous déplacez votre poids et bougez votre corps, les mécanismes de votre équilibre travaillent pour vous garder debout et stable (Aggarwal & Cai, 1999). Dans le contexte de la marche, qui fait référence au schéma de mouvement pendant la marche, l'équilibre dynamique est d'une importance capitale. (Neptune & Vistamehr, 2019). La marche est une activité motrice complexe qui nécessite la coordination des mouvements de divers segments corporels tout en maintenant la stabilité et l'équilibre (Shimada et al., 2003).

Le cycle de la marche est généralement divisé en deux phases principales : la phase d'appui et la phase d'oscillation. La phase d'appui est la période pendant laquelle le pied est en contact avec le sol. Elle représente environ 60 % du cycle de la marche et est elle-même divisée en plusieurs sous-

phases (contact initial, réponse à la charge, mi-phase d'appui, phase terminale d'appui et pré-oscillation). Au cours du cycle de la marche, le pied passe d'une attaque du talon à un décollage des orteils. La phase d'oscillation est la période pendant laquelle le pied n'est pas en contact avec le sol. Elle représente environ 40 % du cycle de la marche et est également divisée en sous-phases (oscillation initiale, mi-oscillation et oscillation terminale) (Tunca et al., 2017). Ces phases créent un cycle continu, car une jambe passe à la suivante dans le cycle (Kharb et al., 2011).

Pendant le cycle de la marche, il y a des moments où un pied est en l'air et le corps est en équilibre sur l'autre jambe. On appelle cela la phase de support sur une seule jambe. L'équilibre dynamique garantit que le corps reste stable et centré sur la jambe de support pendant cette phase, empêchant ainsi une perte d'équilibre (Neptune & Vistamehr, 2019; Patton et al., 1999). Comme mentionné précédemment, le concept du pendule inversé est souvent utilisé pour expliquer et analyser l'équilibre dynamique et la stabilité impliqués dans le maintien d'une posture debout pendant le cycle de la marche (Kuo, 2007). Pendant la phase d'appui de la marche, lorsque l'un des pieds est en contact avec le sol, le centre de masse du corps se déplace vers l'avant. Cela imite l'idée d'une chute contrôlée du pendule inversé. Tout comme une force contrôlée est appliquée pour empêcher le pendule inversé de basculer, nos muscles et notre système nerveux effectuent des ajustements précis pour nous empêcher de tomber en marchant. Le centre de masse du corps humain est analogue au point de pivot du pendule inversé. À mesure que le centre de masse du corps se déplace vers l'avant, il crée une rotation vers l'avant. Le moment et l'emplacement de chaque pas jouent un rôle dans le maintien de la stabilité, tout comme l'ajustement de la base d'un pendule inversé pour le maintenir droit. Le point d'atterrissage du pied contribue à garantir que le centre de masse reste dans une plage de sécurité. La phase de balancement de la marche implique le déplacement de la jambe vers l'avant en préparation pour la prochaine étape. Cette phase peut être comparée à la montée du pendule inversé, où le pendule s'éloigne de sa position stable

Comme le processus de la marche implique le transfert coordonné du poids du corps d'un membre inférieur à l'autre, l'équilibre dynamique joue un rôle crucial pour faciliter la transition en douceur de la charge, réduisant ainsi le risque de chutes ou de trébuchements lors des déplacements latéraux. L'équilibre dynamique, un concept fondamental en biomécanique, désigne la capacité à maintenir la stabilité et l'équilibre en mouvement. Pour atteindre une efficacité dans ce contexte, il est nécessaire d'assurer un contrôle postural précis, ce qui implique à son tour la modulation de la tonicité musculaire, du mouvement articulaire et de l'orientation corporelle pour contrer les forces externes et maintenir la fluidité du mouvement (Jordan et al., 2007). L'orchestration de la coordination musculo-squelettique et l'optimisation de la force musculaire sont également des composantes essentielles de cet équilibre dynamique. La rétroaction sensorielle constitue un mécanisme essentiel pour garantir des réponses précises aux perturbations et se prémunir contre des adaptations erronées lors de la traversée de terrains irréguliers ou de la rencontre d'obstacles dans l'environnement. Les capacités intrinsèques des individus et les conditions environnementales de la locomotion influencent le cycle de la marche et, par conséquent, ses paramètres (Hernández et al., 2009; Kelly et al., 2008). L'analyse de ce cycle de la marche permet d'évaluer les capacités d'un patient, ce qui peut être fait en analysant son Centre de Masse (CoM), par exemple, ou en utilisant des tests cliniques.

1.2. Evaluation de l'équilibre dynamique

Pour évaluer la démarche, divers paramètres du schéma de marche d'une personne peuvent être évalués. Ces paramètres mettent en évidence la qualité de la marche. Tout d'abord, il est possible d'examiner le mouvement du Centre de Masse (CoM) et sa symétrie pendant les phases de marche répétées, ce qui facilite l'évaluation de l'équilibre dynamique (Akhtaruzzaman et al., 2016; Harris & Wertsch, 1994). Le chemin ou la trajectoire du CoM donne également des indications sur la qualité de la marche. De plus, il est possible d'analyser les paramètres spatiaux, notamment la longueur des pas et des enjambées, la largeur des pas et la cinématique des articulations des membres inférieurs (par exemple, la cheville et le genou). Les paramètres spatiotemporels offrent également des informations précieuses sur la qualité de la marche. Il est possible de quantifier des métriques telles que la vitesse de marche, la durée des phases de support et d'oscillation, la cadence, le temps de double support, le temps de support unique et le modèle talon-pointe. De plus, une évaluation complète de l'activité musculaire et des paramètres cinétiques peut fournir des informations supplémentaires précieuses sur la biomécanique de la marche. Ces quantifications nécessitent des outils tels que des plateformes de force ou de pression, des systèmes de capture de mouvement, des caméras et de l'électromyographie (EMG). Les systèmes de capture de mouvement peuvent suivre les mouvements de marqueurs réfléchissants placés sur le corps pour créer une analyse tridimensionnelle détaillée de la marche (et le calcul du CoM) (Pfister et al., 2014). Cela peut fournir des informations sur les angles articulaires, la longueur de l'enjambée, la largeur des pas et d'autres paramètres liés à l'équilibre dynamique. Les plateformes de force ou de pression sont des dispositifs qui mesurent les forces, le moment ou la répartition des pressions exercées par les pieds pendant la marche (Klöpfer-Krämer et al., 2020; White et al., 1999). Ils peuvent fournir des données sur la répartition des forces, le moment du transfert de poids et la stabilité du centre de pression au fur et à mesure du cycle de la marche. Les capteurs portables, tels que les accéléromètres ou les gyroscopes, peuvent fournir des données en temps réel sur les schémas de marche, les caractéristiques des pas et l'équilibre pendant la marche. La mise en œuvre de ces dispositifs et le traitement des données mesurées ne permettent pas toujours leur utilisation optimale en milieu clinique. Les nouvelles technologies apportent de nouveaux outils conviviaux et plus respectueux de l'environnement (Davis et al., 1991; T. Liu et al., 2009; Tong & Granat, 1999; Whittle, 1996). Il existe d'autres moyens d'évaluer la marche en plus de l'analyse du centre de masse et des données des caméras ou de l'EMG. Les cliniciens peuvent observer visuellement la marche d'une personne pour identifier d'éventuelles anomalies, asymétries ou écarts par rapport à un schéma de marche typique. Cela peut inclure la recherche d'une répartition inégale du poids, de changements dans le balancement des bras ou d'une inclinaison excessive du corps. Le test TUG (Timed Up and Go) consiste à chronométrer le temps qu'il faut à une personne pour se lever d'une chaise, marcher sur une courte distance (généralement d'environ 3 mètres), faire demi-tour, revenir à la chaise et s'asseoir (Bohannon, 2006; Savva et al., 2013).

Pour évaluer la marche et l'équilibre dynamique, il est également essentiel de tenir compte de l'intégration multisensorielle. Cela joue un rôle important dans le contrôle de la marche et de l'équilibre (Takakusaki, 2017). L'intégration multisensorielle implique la capacité du cerveau à combiner les informations provenant de différentes modalités sensorielles, telles que la vision, les informations somatosensorielles et le système vestibulaire, afin de créer une perception cohérente de l'environnement et des mouvements du corps. Cette intégration est cruciale pour maintenir la stabilité et ajuster les mouvements (Perrin et al., 2009). La vision fournit des indices essentiels sur l'environnement, tels que les obstacles, les changements de terrain et la position des objets à

proximité. Les retours visuels aident à ajuster la longueur des pas, la position des pieds et l'équilibre pendant la marche (Campos et al., 2012). Le système vestibulaire détecte les changements de position de la tête et les mouvements angulaires, fournissant des informations sur l'orientation de la tête et les mouvements par rapport à la gravité. Ces informations aident à ajuster la posture et les mouvements du corps pour rester debout et maintenir l'équilibre. Les capteurs proprioceptifs dans les muscles, les tendons et les articulations fournissent des informations sur la position, le mouvement et la tension des parties du corps. Cette entrée sensorielle contribue à maintenir les angles articulaires appropriés et l'activation musculaire pendant la marche. Les sensations tactiles et de pression sur la peau fournissent des informations supplémentaires sur le contact entre les pieds et le sol. Ces sensations aident à ajuster les schémas de marche pour s'adapter à différentes surfaces et conditions. L'intégration multisensorielle garantit que les humains peuvent se déplacer efficacement et maintenir l'équilibre, s'adaptant à différents environnements et conditions (Ricotti, 2011; Wegener et al., 1997).

C. Le cas du pied

L'évaluation de l'impact des pieds et de leurs caractéristiques sur l'équilibre statique et dynamique implique d'évaluer comment les indices sensoriels et les mouvements des pieds contribuent à maintenir la stabilité. La manipulation sensorielle du pied implique l'introduction de stimuli contrôlés dans des zones spécifiques du pied. Cette manipulation peut être soit une stimulation, soit une inhibition. Les stimulations peuvent être des vibrations ou des stimuli mécaniques. Les vibrations localisées permettent d'appliquer des vibrations douces à différentes parties du pied. Pendant une tâche statique, les vibrations ont un impact sur les paramètres du CoP en réduisant sa surface ou sa longueur (Schlee et al., 2012). Si les vibrations sont appliquées sur une zone spécifique, comme latéralement sous un pied, le CoP se déplace dans la direction opposée. (Kavounoudias et al., 1998). La vibration du pied peut également induire des modifications du schéma de marche (Yamashita et al., 2021). La stimulation tactile, créée à l'aide de textures ou de variations de matériaux, peut être utilisée pour modifier la sensibilité du pied. Les insoles texturées, par exemple, offrent une sensation tactile différente sous les pieds, ce qui peut influencer la façon dont une personne marche ou se tient debout. Ces modifications peuvent être observées et évaluées pour mieux comprendre comment les sensations tactiles influencent l'équilibre et la stabilité lors de la marche ou de la station debout (Christovão et al., 2013; Maurer et al., 2001).

Il est également possible de réduire l'information ou d'analyser une population atteinte de neuropathie périphérique, telle que les patients diabétiques (Kars et al., 2009; Meyer et al., 2004; Paton et al., 2016). Une manière de réduire l'information est l'anesthésie, qu'elle soit invasive ou non. L'anesthésie de la plante du pied signifie une perte de sensation ou de sentiment dans cette zone. Cette perte de sensation affecte la capacité à percevoir le toucher, la pression et d'autres indices sensoriels du sol, ce qui rend difficile la perception de la position du corps et la réalisation d'ajustements appropriés pour l'équilibre. Cela présente des défis en raison de la nécessité de procédures invasives ou de protocoles prolongés et complexes pour maintenir une inhibition sensorielle constante tout au long de l'expérience au sein et entre les participants (Magnusson, Enbom, Johansson, & Pyykkö, 1990; Magnusson, Enbom, Johansson, & Wiklund, 1990; Meyer

et al., 2004). L'anesthésie du pied induit également des modifications dans l'analyse de la démarche. Cela montre que les récepteurs cutanés du pied jouent un rôle dans l'information du système nerveux central sur l'emplacement du pied, ou participent au processus de ralentissement (Perry et al., 2001).

L'un des outils les plus utilisés est le coussin de mousse pour évaluer l'influence somatosensorielle sur le contrôle de l'équilibre. Le coussin de mousse est constitué d'une surface instable et rembourrée conçue pour créer un environnement instable. On demande au participant de se tenir debout sur le coussin de mousse tout en gardant l'équilibre. Ce phénomène est analysé à l'aide de la mesure du CoP entre les conditions. Cet exercice met à l'épreuve la capacité du corps à maintenir l'équilibre en raison de la surface instable et en perpétuel mouvement (Mancini & Horak, 2010; Nashner, 1982; Sober & Sabes, 2003). Le quotient plantaire (QP) est une mesure qui évalue la différence de mouvement du CdP lorsqu'une personne se tient debout sur une surface instable (comme de la mousse) par rapport à une surface stable (comme un sol dur). Les coussinets en mousse plus épais rendent la tâche plus difficile, tandis que les coussinets plus fins sont utilisés pour évaluer les informations plantaires et offrent moins de proprioception de la cheville que les mousses plus épaisses (Bisson et al., 2014). Cependant, il est essentiel de noter qu'aucun coussin en mousse n'a été validé comme étalon-or pour l'évaluation de l'équilibre. Il existe différents types de mousse, dont l'épaisseur et la dureté ont un impact significatif sur le contrôle de l'équilibre (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; B. Liu et al., 2018; Patel et al., 2008). Les cliniciens disposent d'un large éventail de choix de mousses, ce qui entraîne une variabilité entre les patients et les cliniciens et rend difficile la comparaison des diagnostics ou la formulation de conclusions uniformes. Une réponse non physiologique sur une mousse fine peut indiquer une intégration différente des informations relatives au pied. En règle générale, un coussin en mousse représente un défi pour le contrôle de l'équilibre. Si un patient fait preuve d'une plus grande stabilité sur le coussin de mousse que sur le sol, cela peut indiquer une inefficacité podale, conduisant à des réactions posturales différentes lors de l'utilisation d'orthèses plantaires (Foisy & Kapoula, 2017). Cela peut impliquer un choix thérapeutique dans le traitement des orthèses plantaires.

Les orthèses plantaires sont multiples et leur choix dépend du patient ou de la pathologie (Bonanno et al., 2017). Elles sont fabriquées sur mesure par les podologues. Les matériaux et les formes sont multiples avec des propriétés spécifiques (élasticité, densité, épaisseur). Les orthèses plantaires conçues sur mesure peuvent redistribuer la pression sur le pied. Une répartition équilibrée de la pression peut contribuer à une meilleure stabilité en position statique. Les semelles dotées de caractéristiques telles que des talonnettes, un soutien de la voûte plantaire et des coussinets métatarsiens peuvent améliorer la stabilité générale du pied. Un pied stable peut mieux supporter le poids du corps et minimiser le besoin d'ajustements constants pour maintenir l'équilibre. Certaines semelles sont conçues avec des éléments sensoriels qui stimulent les récepteurs. Ce retour d'information sensoriel accru peut améliorer la proprioception, rendant les individus plus conscients de la position de leur corps et leur permettant de faire des ajustements subtils pour maintenir l'équilibre (Christovão et al., 2013; Palluel et al., 2008; Perry et al., 2000; Roll et al., 2002).

Les semelles qui favorisent une posture plus alignée peuvent avoir un impact indirect sur l'équilibre statique en réduisant les ajustements posturaux inutiles pendant la station debout. Il est important

de noter que l'impact des semelles sur l'équilibre statique peut varier d'une personne à l'autre. Des facteurs tels que la biomécanique individuelle, la structure du pied et toute condition existante doivent être pris en compte lors de l'évaluation des effets des semelles sur l'équilibre. En fait, les semelles intérieures ne produisent pas toujours le même effet sur les individus. Le soutien de la voûte plantaire, par exemple, soutiendra le pied moyen et aura un impact sur la proprioception du pied et de la cheville. Les semelles ont un impact sur l'alignement du pied, ce qui influence l'équilibre dynamique. Cependant, les études se concentrent sur différentes semelles avec des objectifs multiples et sur les patients. Certaines semelles comprennent des éléments fins (quelques millimètres) pour stimuler la zone du pied (Chen et al., 2014). Basés sur l'effet d'une stimulation électrique, ils sont censés avoir le même impact. L'EMI® (Elément médio-interne) est l'un d'entre eux. Cet élément est placé sous la voûte plantaire. Peu d'études ont travaillé sur ceux-ci. On peut observer un déplacement controlatéral du CoP lorsque l'élément est positionné sous le pied. Ce résultat a été obtenu sur une petite population d'adolescents. Une analyse sur une plus grande cohorte est nécessaire pour valider le résultat et mieux comprendre le fonctionnement de l'élément (Janin & Dupui, 2009). Les semelles texturées peuvent également stimuler les récepteurs du pied et avoir un impact sur l'équilibre statique et dynamique (Alfuth, 2017; Hatton et al., 2009, 2012; Ma et al., 2016; Wilson et al., 2008). L'apport sensoriel accru des semelles texturées peut entraîner une plus grande activation des muscles responsables du maintien de l'équilibre. Les muscles des pieds, des chevilles et de la partie inférieure des jambes s'engagent plus activement pour répondre au retour sensoriel, ce qui améliore la stabilité. Ces informations sensorielles accrues permettent au cerveau d'effectuer des ajustements plus précis pour maintenir une posture droite (Kenny et al., 2019). La surface texturée des semelles stimule les récepteurs proprioceptifs des pieds, ce qui entraîne une activation spécifique des muscles des membres inférieurs (Robb & Perry, 2022).

Cela peut conduire à une amélioration des réactions d'équilibre pendant la marche (Aruin & Kanekar, 2013). Les personnes peuvent ajuster subtilement leur démarche en faisant des pas plus courts ou en modifiant leur foulée pour s'adapter au retour sensoriel. D'un autre côté, marcher sur une surface souple met à l'épreuve l'équilibre dynamique. L'adaptation proprioceptive concerne les articulations des membres inférieurs (hanche, genou et cheville). Le schéma de marche et les mouvements du centre de gravité sont modifiés par les surfaces souples (MacLellan & Patla, 2006) pour permettre au SNC de maximiser la stabilité. Les terrains accidentés induisent une adaptation biomécanique de la démarche (Voloshina et al., 2013). Les conclusions sur l'équilibre statique et dynamique sont donc difficiles à généraliser (Christovão et al., 2013; Lourenço et al., 2013) du à la différence sur les orthèses plantaires ou les populations.

Synthèse et objectifs

Dans le domaine de la biomécanique et de la podologie, le pied, équipé d'un ensemble de capteurs cutanés, joue un rôle essentiel en fournissant des informations vitales sur la nature de la surface sur laquelle un individu se tient debout ou se déplace (Shumway-Cook & Woollacott, 2007). La capacité à maintenir un contrôle postural efficace et une stabilité dynamique est primordiale pour effectuer les activités courantes de la vie quotidienne. L'utilisation de semelles orthopédiques représente une stratégie viable pour améliorer le contrôle postural et dynamique en rectifiant les écarts et en stimulant des zones spécifiques pour induire des modifications bénéfiques. Cependant, une question cruciale se pose : Comment évaluer systématiquement la capacité du système plantaire à intégrer efficacement les informations sensorielles qu'il reçoit. L'évaluation des informations sensorielles plantaires peut être réalisée à l'aide de différentes méthodologies. Traditionnellement, pour quantifier l'impact de ce système sur le contrôle postural et moteur, un coussin de mousse est interposé entre les pieds et la surface d'appui. La perturbation induite par ce coussin de mousse est évaluée en analysant le déplacement du CdP. Cette perturbation remet en cause le système sensori-moteur et engendre une instabilité (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; Preszner-Domjan et al., 2012). Malheureusement, il n'existe pas de protocole de test de référence universellement reconnu dans ce contexte. Si le positionnement des sujets et les instructions sont relativement cohérents dans la littérature (par exemple, pieds placés à un angle de 30°, regard fixe, bras le long du corps et enregistrement des données pendant 30 secondes), il existe une grande variabilité dans le choix des matériaux en mousse d'une étude à l'autre. En outre, il n'existe pas de recommandations spécifiques concernant l'épaisseur de la mousse, malgré le fait incontestable que ce paramètre influence profondément les réponses posturales et la cinématique du centre de pression. En outre, les caractéristiques intrinsèques des matériaux restent souvent non spécifiées ou varient d'une étude à l'autre. Il a été démontré que les modifications de la dureté des matériaux ont des effets perceptibles sur les réponses des sujets lors de tâches statiques (Boonsinsukh et al., 2020; Patel et al., 2008). Il est donc impératif d'établir des normes précises pour évaluer l'intégration sensorielle plantaire au sein d'une population saine. Cette normalisation facilitera l'identification des sous-populations manifestant des réponses atypiques.

En outre, l'épaisseur de la mousse a été identifiée comme un facteur significatif influençant l'activité du système proprioceptif (B. Liu et al., 2018). Par conséquent, l'évaluation du système cutané plantaire de manière isolée est jugée irréalisable. Néanmoins, la minimisation de la stimulation proprioceptive permet d'optimiser l'utilisation des autres systèmes sensoriels impliqués dans le contrôle postural. En modifiant exclusivement l'évaluation par l'utilisation d'un coussin de mousse, il devient possible d'accentuer la visualisation de l'influence exercée par le système cutané plantaire et son amalgame dans le cadre plus large du contrôle moteur. Néanmoins, la sélection de matériaux en mousse appropriés est une tâche ardue en raison de la myriade d'options disponibles, ce qui rend difficile la justification des choix (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; Patel et al., 2008). Par conséquent, l'acquisition de données plus détaillées concernant ces matériaux est impérative pour permettre des décisions éclairées. La sélection d'une épaisseur de mousse fine est particulièrement motivée par l'objectif d'obtenir une évaluation spécifique du

système somatosensoriel tout en s'alignant sur les pratiques podologiques actuelles (Foisy & Kapoula, 2017). Notamment, les praticiens français utilisent couramment des tampons de mousse d'une épaisseur de l'ordre de quelques millimètres lorsqu'ils évaluent l'intégration des informations sensorielles plantaires.

L'intégration des informations visuelles représente une facette supplémentaire qui mérite d'être explorée. Il a été démontré que les informations visuelles présentées aux participants exercent une influence profonde sur le contrôle postural (Kapoula & Lê, 2006; Raffi & Piras, 2019; Taneda et al., 2021). Par exemple, la condition "yeux fermés", largement documentée dans la littérature, entraîne une augmentation significative des oscillations du centre de pression, d'environ 30 %, par rapport à la condition "yeux ouverts" (Abrahamová & Hlavačka, 2008; Black et al., 1982). Cependant, il est essentiel de reconnaître que des facteurs tels que la présence d'une cible visuelle, la nature de la cible ou sa distance par rapport au participant peuvent introduire des modifications distinctes dans le contrôle postural (van Asten et al., 1988). Par conséquent, la mise à disposition par inadvertance d'informations visuelles, telles que des affiches ou des peintures dans l'environnement de test, peut donner lieu à des résultats disparates entre les praticiens. Il est donc primordial de bien comprendre ces modifications et leurs implications pour normaliser les procédures de test. Après avoir obtenu des résultats dans un environnement contrôlé impliquant l'utilisation d'un coussin de mousse, le concept de "quotient plantaire" apparaît comme une mesure précieuse. Ce quotient exprime le rapport entre la modification du déplacement de la CdP induite par la perturbation causée par le coussin de mousse (Foisy & Kapoula, 2017). Par conséquent, il sert d'indicateur quantifiable de l'impact de la mousse sur le contrôle postural statique, de manière analogue à la façon dont le quotient de Romberg signifie la modification visuelle (yeux fermés) par rapport à la condition de contrôle (yeux ouverts). Ces quotients permettent une analyse structurée de l'ampleur de la perturbation. Il est classiquement admis que lorsque le quotient plantaire est inférieur à l'unité, il s'agit d'une déviation de l'intégration plantaire physiologique. Ainsi, l'établissement de normes au sein de la population adulte en bonne santé permettra de définir des repères plus fins pour ce ratio. Si cette intégration est jugée non physiologique, on peut raisonnablement s'attendre à des résultats différents lors de la mise en place d'une semelle orthopédique.

Par ailleurs, Foisy & Kapoula (2017) évoquent une intégration modifiée des informations plantaires lors de l'introduction d'une semelle orthopédique, sur la base des résultats du quotient plantaire. Cependant, les informations visuelles très spécifiques fournies aux participants de cette étude soulèvent des questions pertinentes. Si l'on considère exclusivement la modification de l'entrée sensorielle plantaire par le biais d'un coussinet en mousse, le quotient plantaire révèle-t-il effectivement une altération de la capacité à intégrer l'information présentée ? Par ailleurs, les résultats du quotient plantaire peuvent-ils être exploités pour affiner les modalités de traitement orthopédique ou en évaluer l'efficacité ?

Enfin, il est impératif de reconnaître que l'analyse du quotient plantaire et de son association avec les semelles orthopédiques a principalement été menée dans un cadre statique. Or, les exigences de la vie quotidienne impliquent invariablement des mouvements dynamiques, en particulier lors de la locomotion. Il existe diverses méthodologies pour l'analyse de la marche humaine. L'évaluation du déplacement du centre de gravité donne une idée de la trajectoire du sujet. Dans les tâches locomotrices simples telles que la marche linéaire ou les virages singuliers, une

trajectoire stéréotypée discernable émerge. Il est intéressant de noter que le retrait des informations visuelles dévie cette orientation stéréotypée, entraînant une réduction de la précision de la trajectoire du centre de masse (CoM). Il convient de noter que les semelles orthopédiques transmettent des informations sensorielles au système plantaire à chaque phase du cycle de marche.

En conclusion, nous avons mis en évidence les considérations multiples entourant l'évaluation du système sensoriel plantaire, en particulier dans le contexte des interventions liées aux semelles orthopédiques. Elle souligne la nécessité de protocoles d'évaluation normalisés, la quantification des perturbations sensorielles au moyen d'indices tels que le quotient plantaire, et la reconnaissance de l'interaction entre les modalités sensorielles, y compris les informations visuelles, dans l'élaboration du contrôle postural. En outre, elle souligne la nécessité d'étendre ces évaluations au-delà des conditions statiques pour englober des scénarios locomoteurs dynamiques, permettant ainsi une compréhension plus complète des processus complexes qui sous-tendent le contrôle de la posture et du mouvement chez l'homme.

L'objectif principal de la recherche est d'acquérir systématiquement des données normatives caractérisant les modifications induites par l'application d'un mince coussin de mousse sur une cohorte de sujets sains. L'acquisition de ces repères normatifs a pour objectif fondamental de permettre l'identification des réponses atypiques. Cet objectif vise à distinguer les individus qui manifestent une perturbation posturale minimale de ceux qui présentent des fluctuations posturales prononcées en réponse à l'intervention du coussin de mousse. L'objectif principal est de comprendre dans quelle mesure les individus se fient à leur sensorialité plantaire pour maintenir l'équilibre postural. Le deuxième objectif consiste en une exploration systématique de la manière dont les altérations de l'information visuelle introduisent des perturbations dans le contrôle postural statique. Cette ligne d'enquête revêt une importance cruciale pour la normalisation des protocoles d'évaluation et vise à élucider l'influence potentielle de l'environnement visuel sur les modifications observées induites par le coussin de mousse. Plus précisément, il s'agit d'identifier les altérations spécifiques des indices visuels qui perturbent le contrôle postural statique, contribuant ainsi à l'amélioration de la méthodologie.

Le troisième objectif consiste à évaluer si le quotient plantaire, une mesure quantifiée reflétant l'influence du coussin de mousse sur le contrôle postural statique, peut servir d'outil prédictif pour l'intégration des informations sensorielles podales, y compris les effets des interventions orthopédiques telles que les semelles orthopédiques. Cet objectif implique la sélection délibérée de participants présentant des résultats divergents en termes de réponses au quotient plantaire. Ce faisant, il cherche à élucider si les individus dont les résultats du quotient plantaire varient manifestent également des réponses différentielles à l'intégration d'interventions orthopédiques. Cette évaluation englobe à la fois des conditions posturales statiques et des tâches locomotrices dynamiques. En résumé, cette recherche s'efforce de faire progresser notre compréhension de l'interaction complexe entre les entrées sensorielles, avec un accent particulier sur le système plantaire, et les informations visuelles dans la formation du contrôle postural statique et de la locomotion au sein d'une population en bonne santé. L'établissement de données normatives, l'exploration des perturbations visuelles et l'évaluation du potentiel prédictif du quotient plantaire contribuent collectivement à une compréhension scientifique globale de ces interactions complexes. En outre, les résultats peuvent avoir des implications pratiques pour la conception et la personnalisation des interventions, telles que les semelles orthopédiques, visant à optimiser le

contrôle postural et la locomotion au sein de diverses populations. Les résultats de la recherche contribueront à l'élaboration d'un protocole normalisé pour l'évaluation des informations sensorielles plantaires dans des conditions statiques. Cela facilitera le suivi longitudinal des patients dans le temps et améliorera la comparabilité des résultats entre les différents praticiens.

Chapitre 2: Évaluation de la fonction plantaire et de son interaction avec les informations visuelles

Etude 1: Evaluation de l'effet de la plaque de mousse

Dans le contexte de la podologie, l'objectif thérapeutique peut englober de multiples aspects lors de l'évaluation de l'information plantaire. Il permet par exemple de déterminer la présence d'une neuropathie périphérique. Notre objectif est étroitement lié à l'utilisation des semelles orthopédiques. L'évaluation de la fonctionnalité des thermorécepteurs et des nocicepteurs n'est pas l'objet de cette analyse. Notre objectif est de déterminer si la capacité des mécanorécepteurs plantaires peut être évaluée et liée à une intégration spécifique des informations de l'orthèse. C'est pourquoi nous nous intéressons à l'évaluation des mécanorécepteurs. Des évaluations de laboratoire telles que la neuromicrographie sont disponibles, mais nous avons choisi de travailler avec des tests cliniques pour fournir des informations et des outils aux thérapeutes (Strzalkowski et al., 2018).

Les tests cliniques utilisés permettent d'évaluer le fonctionnement des mécanorécepteurs. Le test de discrimination est l'un de ces tests, qui donne des indications sur la capacité à discriminer deux points sur une zone cutanée testée. Ces tests cliniques sont réalisés lorsque les sujets sont assis et ne permettent pas de visualiser le dysfonctionnement de l'intégration du système de contrôle postural. Pour réaliser cette évaluation, les praticiens utilisent des coussins en mousse. Avec cette interposition, les récepteurs cutanés plantaires perçoivent des informations moins précises en raison de la compliance de la surface au sol. Cette compliance entraîne une indentation de la surface lorsque le poids du sujet est appliqué. Cette indentation perturbe le système d'équilibre, qui se réajuste pour corriger la posture et maintenir l'équilibre. En fonction de l'ampleur de la perturbation, les différents systèmes impliqués fourniront également des informations sur le degré de changement par rapport à la situation initiale, ce qui permettra d'ajuster la réponse. Le choix de la mousse est donc crucial. Ses caractéristiques peuvent entraîner des degrés variables d'implication de ces systèmes connexes. Il n'est pas possible d'éliminer les informations fournies par le système vestibulaire ou le système proprioceptif. Cependant, l'utilisation d'une mousse épaisse à haute compliance entraînera un enfoncement plus important lors du positionnement du sujet, conduisant à une augmentation du déplacement du centre de pression induit par les mouvements de balancement du sujet. Par conséquent, le système proprioceptif sera plus alerte, ce qui augmentera son implication dans la régulation de l'équilibre statique.

Il en va de même pour le système vestibulaire, avec une augmentation des oscillations. L'utilisation d'une mousse fine est une solution pour minimiser l'implication d'autres systèmes, en "isolant" efficacement le système de la peau plantaire autant que possible. Définir ce qui constitue une "mousse fine" est abstrait et doit être replacé dans le contexte de l'exercice proposé et de la population choisie. Comme nous l'avons déjà mentionné, la multitude de choix rend les comparaisons entre études complexes. Pour faciliter les comparaisons avec d'autres données, nous

avons choisi d'utiliser une mousse déjà étudiée dans la littérature (Dujols, 1991; Foisy & Kapoula, 2016, 2017): Dépron®, qui mesure 6 mm d'épaisseur. Cependant, il ne s'agit pas d'une mousse utilisée en podologie mais dans la construction. Elle ne possède pas une grande élasticité et la compression induite par le poids d'un individu est maintenue même sans ajout de masse. Elle n'est donc pas réutilisable. Il serait intéressant de trouver une mousse réutilisable à des fins écologiques qui induise le même effet sur l'équilibre statique. En ce qui concerne les informations visuelles, comme pour la mousse, les caractéristiques utilisées pour l'environnement visuel dans la littérature sont variées. La distance par rapport au mur n'est souvent pas précisée, pas plus que la qualité du mur. Lorsqu'une cible visuelle est positionnée, sa forme ou sa texture n'est pas systématiquement rapportée. Or, tous ces paramètres affectent la stabilité du sujet. Pour permettre des comparaisons avec des situations réelles, deux conditions visuelles semblent justifiées : une condition "yeux ouverts" et une condition "yeux fermés". La situation de contrôle, qui correspond à la vie quotidienne et que l'on retrouve également dans la littérature, est une situation où le sujet se tient debout sans aucune modification des informations provenant de l'un ou l'autre des systèmes. Les "yeux ouverts" sans coussin de mousse sont considérés comme l'état neutre. La suppression des informations visuelles associée à la perturbation causée par le coussin de mousse devrait donc normalement être la situation la plus perturbante dans les conditions proposées, contrairement à la situation de contrôle.

Discussion

Nous souhaitons évaluer l'effet d'un mince coussin de mousse sur le contrôle postural chez des adultes en bonne santé, afin de spécifier des valeurs de référence pour des applications cliniques. En outre, nous aimerions comparer l'effet de deux mousses réutilisables et utilisées en clinique avec le Depron®, initialement utilisé pour calculer le quotient plantaire, mais qui n'est pas un matériau réutilisable. Premièrement, l'analyse de l'intégration des pieds à l'aide du test de discrimination en deux points a donné des résultats cohérents avec la littérature existante (Rinkel et al., 2017). Il semble que la sensibilité soit plus précise lorsqu'on évalue la discrimination du talon aux orteils et du milieu aux côtés latéraux du pied. Les pieds sont similaires les uns aux autres. En ce qui concerne le quotient de Romberg, qui évalue le rôle de l'information visuelle dans l'équilibre debout, nous avons observé une augmentation des valeurs des paramètres du CdP (environ 30%) qui est la réaction normale de perturbation, montrant que nos participants ne souffraient pas d'un problème d'intégration de l'information visuelle.

Tout d'abord, les résultats ont montré que les trois mousses utilisées dans cette étude n'induisaient qu'une perturbation minimale du contrôle postural. En effet, en considérant la longueur ainsi que l'entropie approximative du déplacement du CdP pendant une tâche de 30 secondes en position debout, les résultats n'ont pas montré d'effet de la mousse. De plus, en considérant le quotient plantaire (PQ, c'est-à-dire le rapport entre la variable COP avec et sans mousse) pour la longueur du trajet CoP, les valeurs calculées étaient respectivement de 1,02 pour Depron® et de 1,01 pour Orthomic® et Plastazote® (avec les yeux ouverts). L'ampleur de l'effet de la condition de la mousse était de 0,026. Même si l'analyse post hoc a montré une différence significative entre Depron® et Plastazote®, l'impact de la mousse semble marginal. Cependant, comme Depron® et Orthomic® ont des résultats plus proches sur le test d'indentation que Plastazote®, la caractéristique de viscoélasticité de la mousse semble créer un impact minimal sur l'équilibre statique et devrait être prise en compte dans les études.

Ces résultats ne sont pas conformes à la littérature qui a démontré que la mousse est une perturbation constante de la stabilité posturale (Abrahamová & Hlavačka, 2008; Bressel et al., 2007; Fujimoto et al., 2012; Hammami et al., 2014). Toutefois, comme indiqué dans l'introduction, les caractéristiques de la mousse ne sont pas uniformes. L'épaisseur de la mousse varie selon les protocoles. Dans notre étude, nous avons utilisé une mousse fine pour limiter l'utilisation des muscles des membres inférieurs et ensuite évaluer la perturbation des mécanorécepteurs plantaires. Si nos résultats n'ont pas permis de mettre en évidence un effet de la mousse sur le contrôle postural, ils peuvent suggérer qu'il pourrait y avoir une épaisseur minimale pour déstabiliser la posture. De plus, nos résultats ne sont pas en adéquation avec des travaux antérieurs utilisant la mousse Depron® montrant un effet de la mousse sur le PQ, qui était égal à $1,12 \pm 0,39$ (en considérant le paramètre de surface moyen) (Foisy & Kapoula, 2017). Si nous considérons le paramètre de surface moyen, nous obtenons $1,11 \pm 0,62$ yeux ouverts et $1,17 \pm 0,9$ yeux fermés, ce qui est proche des travaux précédents, mais l'IC95% pour ce paramètre est respectivement de [1,02;1,33] yeux fermés et [1,01;1,22] yeux ouverts. Nos distributions ne sont cependant pas les mêmes. Nous obtenons une distribution de type gaussien sans qu'aucune sous-population ne soit mise en évidence. Pour mieux comprendre ces différences, nous avons proposé une analyse supplémentaire similaire à cette étude. Nous avons ensuite divisé notre population en deux groupes sur la base des résultats du PQ : <1 ou >1 , comme dans cet article. Pour ce faire, nous nous sommes basés sur les valeurs moyennes de la surface et de la longueur du déplacement du CdP mesurées au cours des 3 répétitions pour calculer les variables de la QP. Nous avons également pris en compte la valeur minimale de la longueur du déplacement de la CdP pour la comparer à notre propre analyse. First, the repartition of participants is different regarding the CoP parameters considered: Average surface showed the following distribution of participants: $PQ<1=64$ and $PQ>1=67$. En comparaison, les QP calculés avec la longueur de déplacement des CdP, les distributions des participants au sein de ces deux groupes, sont respectivement de 63 et 68 pour la longueur minimale, et de 58 et 73 pour la longueur moyenne. De plus, si l'on considère les participants individuels et leur distribution au sein de chaque groupe de QP (<1 groupe ou >1), 35,9 % n'appartiennent pas au même groupe si l'on compare la surface moyenne à la longueur minimale, 32,1 % si l'on compare la longueur moyenne à la surface moyenne et 32,8 % si l'on compare la longueur moyenne à la longueur minimale. Par conséquent, si les patients sont classés en fonction de leur QP, il est fondamental de se baser sur les mêmes variables pour son calcul. Comme dans la pratique clinique, 3 répétitions ne sont pas souvent effectuées en raison de contraintes de temps, considérer la longueur minimale du déplacement du CdP semble être un choix plus réaliste puisque nous avons donné l'instruction de rester debout aussi immobile que possible.

Si l'on examine de plus près la distribution des PQ dans l'étude précédente, les résultats sont plus proches d'une distribution observée à une distance de 2 mètres du mur. Toutefois, il convient de noter que l'étude précédente a pris en compte les résultats du PQ à une distance de 40 cm du mur. Un autre facteur susceptible d'expliquer les différences avec les travaux précédents est la nature des informations visuelles disponibles. Dans notre étude, nous avons créé un environnement visuel neutre, les participants se tenant à 1 mètre d'un mur blanc sans aucun autre repère visuel.

En revanche, l'article de Foisy et al. a basé ses conditions visuelles sur la distance par rapport au mur (40 cm ou 200 cm) et sur la présence ou l'absence d'une cible visuelle. Il est important de noter que la convergence visuelle est liée à une meilleure stabilité posturale, tandis qu'un champ

visuel texturé est associé à une stabilité plus difficile. Les caractéristiques visuelles de l'environnement expérimental jouent donc un rôle crucial. L'absence d'informations visuelles dans notre protocole pourrait avoir réduit l'impact de la mousse sur la stabilité statique, suggérant que le déséquilibre enregistré pourrait être dû à un déficit dans l'intégration des informations visuelles. Cependant, les informations visuelles peuvent prendre diverses formes et ne sont pas normalisées d'une étude à l'autre. Il est donc essentiel de rapporter soigneusement ces conditions dans les études futures afin de standardiser les procédures et de faciliter la comparaison des résultats.

En conclusion, nos résultats montrent qu'Orthomic® est un substitut écologique au Depron®. En considérant ses normes, les déplacements CoP longueur et sont respectivement de $238 \pm 63,2$ et $237 \pm 63,4$ avec les yeux ouverts et à 1 mètre de distance d'un mur blanc. Mais des informations techniques sur les caractéristiques de la mousse sont nécessaires, telles que la durée de vie de la mousse en fonction de la masse chargée et de la répétition de l'utilisation.

Des travaux futurs sont donc nécessaires pour mieux comprendre la différence entre nos résultats et les travaux antérieurs et feront l'objet des deux prochaines études de ce chapitre. L'information visuelle étant la principale différence entre les deux études, l'évaluation de son impact (champ visuel, convergence) sur la stabilité avec un coussin en mousse pourrait mettre en évidence si une condition visuelle est plus en conflit avec l'information sur le pied. Cela implique de prendre en compte la distance au mur ainsi que le type de cible visuelle. Un autre travail futur pourrait être de comparer les résultats sur le quotient plantaire et l'intégration des informations sur les orthèses plantaires. La distribution du quotient plantaire sur Depron® est continue et limitée entre [0.32;1.57] pour les yeux ouverts dans notre étude. Les travaux futurs pourraient consister à observer différentes sous-populations de cette cohorte. Considérant qu'une réponse normale est un QP autour de $1,02 \pm 0,136$ avec un intervalle de confiance à 95% [0,993 ;1,04], la comparaison d'une sous-population physiologique aux sous-populations extrêmes (QP minimum et QP maximum) sur des semelles orthopédiques pourrait expliquer si le QP est un indicateur utile de l'intégration podale.

Etude 2: Informations visuelles et quotient plantaire

Les informations visuelles transmises principalement par la voie visuelle primaire sont cruciales pour le maintien de l'équilibre. D'autres paramètres visuels ont également un impact sur la posture. La distance à la cible lors d'une position statique influence la stabilité. La stabilité est améliorée lorsque la cible se trouve à 40 cm par rapport à 200 cm (Kapoula & Lê, 2006). L'utilisation d'informations visuelles à haute fréquence et la convergence oculaire renforcent également le contrôle postural. En outre, la perte de la perception visuelle des mouvements entraîne une instabilité posturale. La perte de la perception du champ visuel périphérique entraîne également une réduction de la stabilité, sauf dans le sens antéro-postérieur (Taneda et al., 2021). Le flux visuel permet à un individu de percevoir les mouvements de l'environnement et joue un rôle crucial dans la stabilisation posturale (Raffi et al., 2014). La variation du flux visuel modifie les réponses

posturales. Par exemple, les changements dans la profondeur d'une cible fixe modulent l'instabilité posturale (Kapoula & Lê, 2006). La perception de la mobilité de la cible augmente également l'instabilité (Gautier et al., 2008). Tous ces résultats soulignent l'importance de la prise d'informations visuelles au cours d'une tâche statique.

Les cibles visuelles modifient les réponses posturales. Lorsqu'ils fixent l'une des quatre cibles ayant des effets de profondeur variables, les sujets font preuve d'une plus grande instabilité à mesure que la profondeur de la cible augmente. Le système visuel joue un rôle majeur dans le contrôle et le maintien de la posture (Patel et al., 2011). Cependant, peu d'études fournissent des détails sur les cibles utilisées (taille, forme, motifs) (Fransson et al., 2007; Patel et al., 2008).

Le flux visuel est également un paramètre à prendre en compte lors de l'analyse de l'impact de l'entrée visuelle sur l'équilibre statique. Les mouvements personnels tout en étant debout génèrent un flux optique qui régule la posture. (Gibson, 2014; Neisser, 1994). Le flux optique transporte des informations sur le mouvement des objets externes par rapport à l'observateur et les mouvements de l'observateur par rapport à un environnement stable.

L'interposition de mousse semble augmenter les oscillations posturales (Boonsinsukh et al., 2020; Foisy & Kapoula, 2017; Peterka, 2018). Certaines études ont examiné l'interaction de ces deux systèmes, mais avec différentes conditions expérimentales visuelles. Plusieurs méthodes peuvent perturber les informations plantaires, telles que l'anesthésie, l'hypothermie ou l'interposition de mousse sous la plante des pieds. Cependant, les variations de mousse, en termes d'épaisseur ou de hauteur, ainsi que les variations d'informations visuelles, rendent difficile la comparaison entre les études.. En pratique, de nombreuses mousses différentes avec des caractéristiques différentes peuvent être utilisées, ainsi que différents environnements cliniques (mur, environnement visuel).. Si les réponses obtenues dépendent de la mousse et de la vision, les résultats sont difficiles à extrapoler et à prévoir. Certaines études ont examiné l'interaction de ces deux systèmes, mais avec des conditions expérimentales visuelles différentes. Le travail de Foisy et al (2017) montre qu'un sous-ensemble de leurs participants présente une inefficacité podale : une meilleure stabilité sur la mousse Dépron® (6 mm) que sur un sol dur avec une cible à 40 cm, mais pas avec une cible à 200 cm. Nos travaux précédents n'ont pas mis en évidence d'effet du Dépron® sur la stabilité. Comme nous n'avons pas fourni de cible visuelle, les effets observés dans les études, lorsque les participants sont sur de la mousse, sont-ils liés à une capacité d'information podale ou visuelle ?

L'objectif principal de cette étude est de mieux comprendre l'impact de l'environnement visuel sur l'équilibre statique des adultes en bonne santé, en mettant particulièrement l'accent sur deux facteurs : la distance par rapport au mur et le type de cible présentée. Nous avons cherché à approfondir les recherches menées par Foisy et ses collègues (Foisy & Kapoula, 2017) en examinant différents aspects de l'information visuelle.

Nos hypothèses se concentrent sur l'impact de la distance par rapport au mur. Nous prévoyons que plus la distance par rapport au mur augmente, plus cela entraînera des perturbations dans le contrôle statique. De plus, nous anticipons qu'une cible texturée, qui améliore le flux visuel, entraînera une meilleure stabilité par rapport à d'autres conditions.

Un autre objectif essentiel est d'évaluer l'interaction potentielle entre l'information visuelle et podale (liée aux pieds). Nous émettons l'hypothèse que la présence d'un coussin en mousse,

combinée à des modifications de l'environnement visuel, entraînera un accroissement de l'instabilité chez les adultes en bonne santé. Cette étude vise à explorer l'interrelation entre ces facteurs et comment ils influencent la capacité d'un individu à maintenir un équilibre statique.

Discussion

Nous avons souhaité évaluer l'effet de différentes conditions visuelles sur le contrôle postural chez des adultes en bonne santé, dans le but de comprendre quels paramètres influencent l'équilibre statique et son interaction possible avec une information podale liée à l'utilisation d'un coussin en mousse sous les pieds. Tout d'abord, pour être inclus dans cette étude, il était nécessaire de passer des tests optométriques. Afin d'obtenir 76 adultes présentant une vision physiologique, 145 participants ont été recrutés. Cela représente 47 % de la population initiale qui ne présente pas de troubles visuels physiologiques. La condition d'inclusion est rarement mise en œuvre dans la littérature. Les participants sont interrogés sur la présence d'une pathologie oculaire, auquel cas ils sont exclus de l'étude. Ce pourcentage élevé soulève des questions sur l'uniformité des populations étudiées. En effet, la majorité des individus exclus présentaient des déficits d'accommodation, d'acuité visuelle ou de vergence, mais n'en avaient pas conscience. Il semble qu'un déficit de vergence ait un impact sur le contrôle postural dans les populations pathologiques, telles que les enfants dyslexiques ou les adultes atteints de troubles de la vergence (Bucci et al., 2014; Morize & Kapoula, 2017). De même, une acuité visuelle réduite représente un défi pour le contrôle postural (Sambit et al., 2012). Nous ne savons pas si le pourcentage d'exclusions est normal ou non. L'évaluation a été réalisée par des professionnels à l'aide d'équipements spécialisés, ce qui nécessite une collaboration avec eux pour des analyses plus approfondies de l'impact des troubles de l'accommodation, de l'acuité visuelle ou de la vergence sur l'équilibre statique. La distance entre le participant et le mur induit une modification de l'équilibre statique, avec un meilleur contrôle observé à des distances plus courtes. Ce résultat est obtenu indépendamment de la condition visuelle fournie, que ce soit avec ou sans coussins en mousse sous les pieds. Lorsque le participant a les yeux ouverts sans cible, le flux visuel fournit une évaluation plus précise de son automouvement. Plus ils sont près d'un mur, plus le mur fournit une indication des oscillations effectuées. Tous les protocoles n'ont pas les mêmes distances entre le mur et le participant, et la distance spécifique à laquelle le flux visuel est perçu et impacte l'équilibre statique n'est pas définie. Par conséquent, la comparaison des résultats entre les études est difficile. Explorer la contribution de cette distance et de l'information visuelle dans l'intégration multisensorielle est justifié. De plus, les capacités intrinsèques des participants influenceront également la perception de ce flux. Le manque d'évaluation de cette capacité complique davantage la synthèse des résultats de la littérature.

Dans la situation où les yeux sont fermés, nous observons également une différence dans les oscillations. Sans information visuelle, il semble que la présence d'un mur à proximité améliore le contrôle statique. Nous pouvons émettre l'hypothèse que le risque de collision avec le mur accroît la dépendance au contrôle cognitif de l'individu. Le même résultat est observé lorsque la cible est à 40 cm, mais le mur est soit à 40 cm, soit à 200 cm. Le contrôle de la vergence induit par la cible est donc annulé par l'information de distance fournie par le mur.

Les différentes cibles présentées aux participants ont permis une caractérisation plus précise de l'information visuelle utilisée dans le maintien de l'équilibre statique. Pour rappel, le facteur visuel comportait quatre niveaux : yeux fermés, yeux ouverts sans cibles, une cible ronde et une cible ronde intégrée dans une image de paysage. L'équilibre statique s'améliore lorsque la cible présente une texture devant les participants. Comparée à une simple cible ronde, la texture de l'image semble fournir des informations contribuant à l'équilibre. La texture de cette cible améliore la perception du flux visuel et permet au sujet d'évaluer plus précisément son propre mouvement.

Cependant, nous n'avons pas pu confirmer si les yeux étaient uniquement fixés sur le point rouge. Il est possible que la présence d'une image incite le participant à l'explorer, ce qui pourrait entraîner un renforcement du contrôle cognitif. De plus, cette image était positionnée sur un mur blanc, créant un fort contraste entre l'image et le mur. Cela a entraîné la fourniture d'informations à la fois verticales et horizontales aux participants à travers les contours de l'image. Les informations verticales sont utilisées par le système visuo-vestibulaire pour réajuster l'orientation verticale perçue à la verticale gravitationnelle.

L'objectif de cette étude était de mieux comprendre comment l'information visuelle impacte l'équilibre statique, en particulier lorsque l'on se tient debout sur des surfaces en mousse. Pour nous comparer à la littérature et à une étude précédente (référéncée sous le nom "Étude 1"), nous avons utilisé un coussin Depron® de 6 mm d'épaisseur. Les résultats obtenus ne montrent aucun impact du Depron® sur le contrôle postural. Lors du calcul du PQ, un score plus élevé est obtenu pour la cible texturée, ce qui est conforme aux résultats précédemment présentés concernant l'impact visuel. Si nous comparons les résultats de l'étude 1 et de l'étude 2 sur le PQ (avec les yeux ouverts et les yeux fermés, sur le Depron®), nous obtenons en moyenne \pm l'écart type respectivement $PQ_{Study1} = 1,02 \pm 0,133$ et $1,03 \pm 0,138$ (à 1 mètre du mur), $PQ_{Study2} = 1,01 \pm 0,129$ et $1,06 \pm 0,148$ (à 40 cm du mur), et $PQ_{Study2} = 1,05 \pm 0,140$ et $0,991 \pm 0,126$ (à 200 cm du mur). L'intervalle de confiance à 95% est respectivement [0,993 ; 1,04] et [1,00 ; 1,05] pour l'étude 1, [0,98 ; 1,04] et [1,03 ; 1,09] pour l'étude 2 à 40 cm du mur et [1,02 ; 1,08] et [0,962 ; 1,02] à 200 cm. Les résultats sont d'une ampleur similaire. L'utilisation des informations plantaires pour maintenir l'équilibre chez les sujets ne semble pas être perturbée par l'interposition de la mousse, car tous les PQ sont autour de 1. Nous obtenons une distribution de type gaussien sans sous-population évidente mise en évidence pour tous les PQ calculés.

Cependant, nous observons que l'interposition de la mousse dans la situation "cible à 40 cm et mur à 200 cm" est significativement différente de la situation "cible à 40 cm et mur à 40 cm". L'impact de la distance par rapport au mur semble être réduit lorsque la mousse est interposée, ce que nous n'avons pas constaté lorsque la cible et le mur étaient tous les deux à 200 cm. Il est possible que cette situation exige une attention accrue et permette une expression amplifiée de l'effet de la mousse. Les conditions expérimentales ont en effet influencé les mesures du contrôle statique. Le manque de standardisation dans la littérature concernant l'information visuelle fournie rend difficile l'évaluation objective de la perturbation. La vergence induite par la cible, associée à l'augmentation du flux visuel, permet une meilleure stabilité grâce à une utilisation améliorée de l'information fournie. Bien que le Depron® ne remette pas en cause le système d'équilibre dans ces cas, il semble que l'analyse dans ces situations soit davantage axée sur la capacité visuelle que sur la capacité d'intégration podale. Même si notre population d'étude ne présentait pas de troubles visuels, étant donné les résultats obtenus avec les divers indices visuels fournis, il est intéressant d'explorer si les participants présentent une dépendance visuelle. Il s'agit de la dépendance d'une

personne à l'information visuelle pour maintenir l'équilibre et l'orientation dans leur environnement.

Study 3: Visual field and Plantar quotient

Au cours des deux premières études, nous avons pu observer l'importance de l'information visuelle fournie dans le maintien de l'équilibre. Le système visuel joue un rôle significatif à la fois dans l'équilibre statique et pendant le mouvement (Davlin-Pater, 2010). La dépendance visuelle suggère qu'une personne s'appuie davantage sur les indices visuels que sur d'autres entrées sensorielles, telles que la proprioception ou l'information podale, tout en maintenant l'équilibre statique. Elle est liée à divers aspects du contrôle moteur, tels que l'attention à la tâche et les stratégies de maintien de l'équilibre mises en œuvre. Dans le cas de systèmes non fonctionnels, la dépendance visuelle permet d'identifier les individus qui utiliseront préférentiellement l'information visuelle pour la compensation. L'intégration multisensorielle dépend des capacités intrinsèques de l'individu et de son environnement (Nyborg, 1971a, 1971b). Certaines personnes présentant un degré élevé de dépendance visuelle peuvent rencontrer des difficultés en ce qui concerne l'équilibre et l'orientation lorsque l'information visuelle est limitée ou perturbée. En revanche, certaines personnes n'ont aucune difficulté à maintenir leur stabilité même lorsque l'information visuelle est limitée ou absente. Elles ont un degré moindre de dépendance visuelle (Isableu et al., 2003).

L'évaluation de la dépendance visuelle implique généralement d'évaluer dans quelle mesure un individu s'appuie sur les indices visuels pour l'équilibre et l'orientation par rapport à d'autres entrées sensorielles (Jacobson, 1966). Il est possible de réaliser des tests cliniques ou des mesures sur une plateforme pour évaluer la dépendance visuelle (Torneke, 2010).

Discussion

L'objectif de cette expérience était de déterminer si le quotient plantaire et la dépendance au champ visuel étaient corrélés. Pour rappel, notre population d'étude était composée d'adultes en bonne santé (âgés de 18 à 45 ans) dont l'évaluation orthoptique était conforme aux normes physiologiques. Nous avons émis l'hypothèse que les participants présentant un degré plus élevé de dépendance au champ visuel rencontreraient des difficultés accrues lorsqu'ils se tenaient debout sur un coussin en mousse les yeux fermés. Une augmentation du quotient plantaire aurait été corrélée à la dépendance au champ visuel, avec une corrélation positive significative. Les résultats n'ont pas mis en évidence de corrélation entre ces deux paramètres. Nous avons également comparé le RFT (Ratio of Foam to Time) entre deux conditions podales : contrôle (c'est-à-dire sans mousse) et Depron®. Aucune différence significative n'a été mise en évidence. Ce résultat est cohérent avec les conclusions obtenues dans les études 1 et 2 : l'utilisation de Depron® ne pose pas de défi en matière de stabilisation pour la population étudiée. Sa capacité d'intégration multisensorielle est suffisamment élevée pour éviter toute difficulté. Il semble qu'en dépit de la dépendance au champ visuel chez certains individus, l'information provenant d'autres sous-systèmes soit suffisante pour que leur référence géocentrique soit précise. Cependant, il est possible que le résultat soit différent dans une population plus âgée ou pathologique, où la pondération sensorielle est modifiée en raison des capacités sensorielles diminuées des participants

(Hafstrom et al., 2004; Lopez et al., 2006; Lord & Webster, 1990). De plus, notre expertise n'est pas spécifique au champ visuel, et cette étude visait à ouvrir la voie à de nouvelles expériences potentielles. Il convient de noter les biais méthodologiques, notamment le nombre probablement insuffisant de répétitions et l'utilisation d'un seul test d'évaluation. Notre choix a été guidé par la possibilité de réaliser ce test dans la routine clinique. Cependant, une analyse plus détaillée avec d'autres tests est nécessaire pour tirer des conclusions plus concluantes. Il semble toutefois nécessaire de prendre en compte l'ensemble de ces informations visuelles avant de tirer des conclusions sur l'équilibre statique de nos patients placés sur des coussins en mousse mince.

Discussion

L'objectif de ce chapitre était de mieux comprendre l'évaluation effectuée par le quotient plantaire et ses interactions potentielles avec l'environnement. Notre objectif était d'établir des normes au sein d'une population en bonne santé afin d'identifier un déséquilibre statique non physiologique.

Le choix de la mousse est un sujet qui nécessite davantage d'exploration. En effet, nous avons choisi de confronter la réalité de la pratique clinique. Cependant, il est possible que ce choix ne soit pas optimal pour évaluer le rôle de l'information cutanée plantaire dans cette évaluation de l'équilibre. Cela nécessite davantage d'informations techniques sur ces mousses et, par conséquent, une collaboration avec des laboratoires d'analyse des matériaux. L'épaisseur choisie est bien entendu sujette à discussion. La hauteur utilisée dans cette pratique clinique est loin des hauteurs de mousse que l'on trouve dans la littérature (Boonsinsukh et al., 2020; Gosselin & Fagan, 2015; B. Liu et al., 2018; Patel et al., 2008). Alors que notre épaisseur de mousse est inférieure à un centimètre, les auteurs de la littérature utilisent couramment des mousses d'une épaisseur minimale de plusieurs centimètres. La difficulté de l'équilibre statique est donc accrue, ce qui se traduit par des quotients plantaires nettement plus élevés. Dans ces études, la réaffectation sensorielle est différente, avec une information proprioceptive plus alerte. Isoler uniquement le système cutané plantaire semble impossible, ou cela nécessite une analyse couplée entre l'information plantaire et proprioceptive pour déterminer quelles mousses affectent les systèmes et dans quelle mesure. La dureté et l'élasticité de la mousse doivent également être prises en compte. Si la mousse a une faible dureté, le poids placé dessus comprimera davantage le matériau. Si son élasticité est élevée, lors de mouvements oscillatoires, la mousse retrouvera sa forme initiale entre deux supports. Le retour à la forme initiale ou son absence peut potentiellement altérer la réponse future car cela modifie le plan sur lequel l'individu est positionné. Nous n'avons pas pris en compte le poids des participants dans notre analyse. Cependant, plus la mousse est épaisse, plus l'impact de la compression de la mousse entre deux sujets de poids différent est important. À notre connaissance, ce poids n'est pas pris en compte dans le choix de la mousse pour le calcul du quotient plantaire en milieu clinique.

Ainsi, nos résultats sont basés sur une fine mousse d'une épaisseur de 6 mm. Son impact sur l'équilibre statique peut être considéré comme négligeable dans une population d'adultes en bonne santé. En effet, un quotient plantaire (QP) compris entre 0,99 et 1,02 est observé lorsque aucune information visuelle n'est fournie, à moins qu'il n'y ait un mur blanc. Une alternative respectueuse de l'environnement à Depron® pourrait être proposée, car nos résultats obtenus avec Orthomic® sont similaires. Cependant, les conditions expérimentales telles que la distance par rapport au mur et l'impact de l'information visuelle influencent les résultats des sujets en bonne santé. Nous observons notamment des différences dans la condition yeux fermés entre la présence d'un mur à 40 cm et à 200 cm. La conscience du sujet de la distance par rapport au mur altère son équilibre. Les 40 cm peuvent être considérés comme une intrusion dans l'espace personnel. (Hecht et al., 2019). L'information visuelle est un élément majeur du contrôle statique et dynamique. Sa suppression conjuguée à la présence d'un obstacle proche peut certainement induire un état de stress et un renforcement du contrôle de l'équilibre statique. Bien que l'objectif de ce travail soit d'identifier les caractéristiques du quotient plantaire et l'impact de son environnement, il convient de considérer l'évaluation clinique dans son ensemble. Une évaluation clinique devrait prendre en compte la vie quotidienne du patient afin de comprendre l'impact d'un déficit sur sa routine quotidienne. Si notre espace personnel est situé autour de nous dans un diamètre d'environ 1 mètre, il est peu probable qu'une évaluation à 40 cm d'un mur représente une situation cliniquement pertinente. Cependant, cette distance permet une meilleure évaluation de la répartition sensorielle. En effet, des différences sont également observées dans les oscillations des participants les yeux ouverts. Dans cette situation, l'information du mur est présente, et ils sont plus capables de la prendre en compte. Cependant, dès qu'une cible visuelle est ajoutée, les différences entre les conditions deviennent plus marquées. Les cibles visuelles à 40 cm induisent une convergence oculaire forcée. Les informations texturées dans une image renforcent également la perception du flux visuel. Le manque de normalisation dans l'évaluation statique dans la littérature ou le manque d'informations dans les études rend difficile la comparaison des résultats entre différentes études. Pour permettre des comparaisons de l'évolution d'un patient au fil du temps, il est donc nécessaire de normaliser leur environnement de mesure au sein de la clinique. Un changement de décor ou de position de la plateforme par rapport au mur peut entraîner des différences dans les résultats obtenus qui ne sont pas uniquement dus à des changements dans les capacités individuelles. De plus, si les professionnels de la santé veulent être en mesure de discuter de leurs résultats dans cette analyse, il est essentiel d'établir une normalisation afin de comparer les données. Le fait que le QP soit plus élevé avec des informations visuelles spécifiques indique le rôle de la vision dans l'équilibre statique. L'utilisation de l'information visuelle est donc préférée dans ces conditions. Étant donné que Dépron ne semble pas avoir un impact significatif sur toutes les analyses menées, quelles que soient les distances ou les cibles choisies, les résultats de la littérature pourraient refléter davantage une capacité à intégrer l'information visuelle qu'une information plantaire. Sinon, examinons de plus près les résultats de Foisy et al. Le QP et le QR semblent présenter des caractéristiques similaires (pas de chevauchement des données entre les deux sous-populations décrites : inefficace et efficace plantaire). Les résultats de nos deux études (1 et 2) ne nous permettent pas d'identifier deux sous-populations distinctes. Au contraire, la grande majorité des individus ont un intervalle de confiance à 95 % pour la moyenne du QP allant de 0,995 à 1,02. De plus, le choix de la variable utilisée pour calculer le QP modifie la distribution linéaire des participants. Pour mieux comprendre si le quotient plantaire est lié à l'intégration d'un élément

orthétique (chapitre 3), nous avons choisi une situation sans information visuelle supplémentaire pour éviter son impact sur nos résultats.

Le choix de la variable utilisée pour le QP est également un sujet de discussion. Notre choix était basé sur deux facteurs : la stabilité de la mesure entre les répétitions et entre les participants, tout en tenant compte de la praticité des conditions réelles. Les conditions expérimentales sont souvent non écologiques, et peu de podiatres effectuent trois répétitions de chaque condition de pied qu'ils testent. Dans ce contexte, la longueur du déplacement du centre de pression (ou sa vitesse) semble être des paramètres intéressants. Cependant, une analyse plus complète de la capacité d'équilibre statique des patients impliquerait probablement de combiner plusieurs paramètres pour définir un profil plus précis. À cet égard, la plateforme utilisée dans les études du chapitre 2 est une plateforme couramment utilisée dans les cliniques de podologie. Actuellement, le logiciel n'offre pas de couplage de certains paramètres du centre de pression. Bien que nous ayons pris en compte des conditions cliniques réelles, une autre possibilité d'évaluer l'importance de cette information plantaire sur les plateformes de stabilométrie devrait être envisagée. Généralement, pour évaluer le poids de l'information sensorielle, elle est soit stimulée, soit diminuée. L'utilisation de matériaux texturés sur une plateforme peut également être employée. Ce matériau est constitué de petites indentations (dont les diamètres et l'épaisseur peuvent varier dans différentes études). Elles sont réparties à la surface du matériau et agissent davantage comme des points de stimulation. En effet, sur ces zones de support, la pression exercée serait augmentée par les indentations, ce qui entraînerait une plus grande stimulation des mécanorécepteurs. Les matériaux texturés améliorent l'équilibre statique (Kenny et al., 2019). La combinaison de ce matériau avec les yeux fermés donne de meilleures performances en termes de stabilité que sans cette stimulation plantaire. Cette condition laisse de la place pour l'expression de l'information plantaire, car nous savons que l'information visuelle prédomine à la fois dans le contrôle statique et dynamique. Cependant, les résultats montrent également des différences dans le choix des matériaux texturés et des paramètres du centre de pression analysés. De plus, nous n'avons pas tous les détails de l'environnement (visuel et distance par rapport au mur). Alors qu'ils altèrent les résultats lorsque la mousse est interposée, est-ce que le poids de l'information visuelle est le même lorsque les mécanorécepteurs sont stimulés avec des matériaux texturés ? Plus d'études sont donc nécessaires avant de standardiser un PQ sur des matériaux texturés. Cependant, l'aspect écologique mérite également d'être discuté. À l'heure actuelle, peu de fournisseurs de matériaux proposent ce type de matériau (un seul à notre connaissance) en France comme revêtement de semelles. Si nous nous concentrons sur les participants et leurs caractéristiques, l'obtention d'une population homogène est particulièrement difficile. L'acuité visuelle semble être un point important de discussion. En effet, peu d'études sur l'équilibre statique sur des semelles en mousse incluent une analyse optométrique des participants. Notre erreur a été de sous-estimer les déficits visuels dans une population de jeunes adultes et leur manque de conscience à ce sujet. Un objectif visuel proche nécessitera un effort de convergence, tandis qu'une image nécessitera l'accommodation. Les défauts dans ces deux paramètres, par exemple, influencent-ils les résultats dans une population en bonne santé ? Nous savons que lorsque la population étudiée présente des déficits visuels importants, la stratégie d'équilibre est modifiée, et l'équilibre statique est affecté. Les podiatres ne sont pas des spécialistes de la vision et peuvent ne pas être compétents pour réaliser des tests de vision ou interpréter leurs résultats. Cependant, ils devraient considérer que leurs résultats sont

influencés par les capacités du patient, en particulier lors de l'analyse au fil du temps. Notre analyse de la dépendance visuelle n'est pas suffisamment pertinente pour être considérée comme un résultat fiable. Des études futures sont nécessaires. Cependant, la mise en place de ce test en réalité virtuelle est simple et pourrait permettre une analyse en milieu clinique. Tout comme d'autres paramètres modifiés, cette dépendance ne semble pas poser de défi aux participants lorsqu'ils sont sur de la mousse.

Nous savons également que le vieillissement entraîne des difficultés dans l'équilibre statique. Nous aurions pu subdiviser notre population ou considérer différents groupes d'âge pour obtenir des normes au sein de ces catégories.

Dans le prochain chapitre, nous nous concentrerons sur l'intégration d'un élément orthopédique dans la semelle, en nous basant sur les résultats obtenus dans l'Étude 1. En effet, le quotient plantaire a été décrit comme prédictif de la capacité à intégrer l'information plantaire. Par conséquent, nous avons sélectionné trois sous-populations avec différents quotients plantaires. Notre analyse se concentrera sur l'intégration de la semelle à la fois dans des conditions statiques et dynamiques pour fournir une analyse plus écologique des conditions de la vie quotidienne, en particulier pendant la marche.

Chapitre 3: Evaluation d'une stimulation orthétique lors d'une tâche statique et dynamique

Etude 4: Evaluation des semelles orthopédiques

Les semelles orthopédiques sont utilisées par les podiatres pour corriger ou améliorer la fonctionnalité du pied et du membre inférieur lors de la mise en charge (Barnett, 1998). Ils parviennent à cela en introduisant des contours spécifiques conçus pour fournir de nouvelles informations au système de contrôle moteur, modifiant ainsi les rétroactions proprioceptives et sensorimotrices transmises (Becker et al., 2023; Hatton et al., 2013; Mihaela Alina & Corina, 2021). Dans la pratique clinique, l'impact dynamique est principalement évalué lors de tâches locomotrices telles que la marche ou la course. L'impact des semelles orthopédiques est un sujet de discussion dans la littérature. En effet, il existe de nombreuses approches thérapeutiques pour diverses pathologies, et leur évaluation est diversifiée (Barton et al., 2010; Murley et al., 2009). Certaines découvertes indiquent une réduction de la douleur suite à l'utilisation de semelles orthopédiques. (Hawke et al., 2008). De plus, il existe des preuves de modifications de l'activité musculaire des membres inférieurs et d'une réduction de la déviation du pied, par exemple (Alfuth, 2017; Barton et al., 2010; Christovão et al., 2013; Robb & Perry, 2022). Dans leur étude, Foisy et ses collègues ont démontré une relation entre l'intégration de l'information plantaire (telle que

déterminée par le calcul du quotient plantaire) et l'incorporation d'un élément dans les semelles orthopédiques. L'intégration de l'élément d'une semelle orthopédique varierait en fonction du résultat d'oscillation du patient sur une plateforme en mousse fine. Ils classifient les individus ayant un quotient plantaire inférieur à 1 comme "inefficients sur le plan podal" et ceux ayant un quotient plus élevé comme "efficaces" (Foisy & Kapoula, 2017). Ce résultat semble indiquer une capacité physiologique individuelle à assimiler l'information plantaire. Cependant, il est important de noter que cette analyse a été menée uniquement lors d'une tâche statique. L'élément utilisé est un support de voûte plantaire médiale situé dans la voûte plantaire et mesure 3 mm de hauteur. Lorsqu'il est positionné bilatéralement, il induirait des changements dans la zone d'oscillation et la longueur du déplacement du centre de pression. Son intégration au fil du temps modulerait le contrôle moteur après 7 jours (Foisy & Kapoula, 2017; Tramontano et al., 2019). Lorsqu'il est utilisé unilatéralement, il semble modifier la position du centre de pression (CoP) le long de l'axe médio-latéral. Son insertion sous un pied susciterait une réponse posturale en activant les mécanorécepteurs, entraînant un déplacement controlatéral pour rétablir l'équilibre statique (Janin & Dupui, 2009).

Toutes ces analyses avec des éléments aussi fins ont été réalisées dans des situations statiques. Cependant, cette évaluation est loin d'être écologique car le port d'orthèses orthopédiques dans la vie quotidienne implique de les utiliser pendant des mouvements tels que la marche. Pour visualiser l'impact d'un élément d'orthèse orthopédique sur la locomotion, plusieurs analyses peuvent être menées, notamment une évaluation des angles des membres inférieurs, une analyse de l'activité musculaire ou un examen de la trajectoire locomotrice (Alfuth, 2017; Chen et al., 2010; Hajizadeh et al., 2020; Hatton et al., 2013; Jeleń et al., 2008; Mills et al., 2010; Nester et al., 2003). Il est également possible d'examiner le mouvement du Centre de Pression (CoP) le long de la trajectoire en analysant la trajectoire du CoP lors de la marche.

L'objectif de cette étude est d'évaluer l'effet d'un élément orthopédique d'une fine semelle placé de manière unilatérale sur l'équilibre statique et dynamique. La sélection des participants se fera en fonction de leurs résultats de quotient plantaire afin de mieux comprendre si l'intégration plantaire sur une mousse est un indicateur efficace de l'intégration d'un élément de semelle dans les deux situations indiquées. L'étude du déplacement du Centre de Pression (CoP) sera menée le long des axes médio latéraux et antéro-postérieurs, ainsi que de l'aire d'oscillation et de la longueur du déplacement du CoP. L'analyse de la locomotion évaluera l'effet sur l'axe médio latéral de l'élément par rapport à la projection du centre de masse des participants. Cette analyse comprendra des trajectoires simples telles que la marche droite et les virages à 90° à gauche et à droite. Elle se concentrera en particulier sur le moment du contact du pied pendant le cycle de marche et comparera les zones entre le déplacement du point situé au milieu de l'axe "pointe-talon" et le Centre de Masse (CoM).

Discussion

L'objectif de cette étude était de comprendre l'effet d'un élément de semelle orthopédique sur la posture statique et la marche. Le composant de support de l'arche longitudinale médiale a été précédemment décrit dans la littérature comme induisant une latéralisation du Centre de Pression (CoP) dans une posture statique. Premièrement, l'élément ne provoque aucune déviation orientée

du CoP sur l'axe médio latéral. En effet, la déviation se produit uniquement du côté gauche, indépendamment du côté de la stimulation. Cependant, il induit un trouble de l'équilibre caractérisé par des oscillations accrues du Centre de Pression (CoP) et une plus grande longueur de déplacement. Ces résultats sont cohérents avec la littérature existante. Cependant, dans notre cas, il est appliqué de manière unilatérale. Cela suggère qu'un trouble unilatéral n'est pas compensé par le côté non stimulé. Ces résultats soutiennent l'idée d'une intégration globale de la stimulation non directionnelle. Ce résultat, contrairement aux résultats précédents, suggère que cet élément ne peut pas être choisi par le clinicien pour contrer la latéralisation. Il convient de noter que les résultats de l'étude sont surprenants, en particulier en ce qui concerne l'effet de la vision. Alors que dans toutes nos études précédentes et dans la littérature, la condition avec les yeux fermés augmentait les oscillations des participants, dans ce cas actuel, les oscillations sont moins prononcées (tant en termes de surface du CoP que de longueur de son déplacement). Nos participants semblent avoir adopté une stratégie différente par rapport à leur enregistrement initial dans l'étude 1. Le chapitre précédent a montré l'interaction de l'environnement avec l'équilibre statique. Il est possible que les conditions expérimentales aient influencé la réponse. Des facteurs tels que les vêtements des participants et le nouvel environnement ont peut-être conduit à un meilleur contrôle postural avec les yeux ouverts. Nous n'avons pas d'explications supplémentaires pour expliquer cette différence entre les yeux ouverts et les yeux fermés. En ce qui concerne la marche, nous observons également un effet du composant de la semelle orthopédique non directionnelle. Le centre de masse (CoM) des participants est moins dévié latéralement lorsqu'ils sont stimulés par le composant de la semelle orthopédique. Par conséquent, nous avons une intégration de la stimulation plantaire, tant avec les yeux fermés qu'ouverts, lors des foulées successives du cycle de marche. Tout comme dans la condition statique, l'hypothèse d'une réponse directionnelle à la stimulation plantaire est rejetée. En effet, cette stimulation réduit la latéralisation des participants par rapport à la situation de contrôle. On peut supposer que cette stimulation, en activant les mécanorécepteurs plantaires, conduit à un meilleur contrôle de la part du sujet qui réaligne son axe corporel. Ces résultats peuvent être comparés à ceux obtenus avec l'utilisation de semelles texturées. Lorsque des semelles texturées sont portées, une activation musculaire dans la jambe est enregistrée. Par conséquent, nous avons un message plantaire affectant le contrôle dynamique. Les participants, après avoir effectué 18 essais avec chaque stimulation, ne semblent pas montrer une intégration temporelle de celle-ci. Certaines études ont montré un effet amplifié du composant le septième jour après sa mise en place, en particulier dans les tâches statiques. Il serait intéressant de déterminer si l'effet observé en marchant avec la stimulation plantaire persiste après plusieurs jours. Après tout, les semelles orthopédiques sont portées pendant de longues périodes, il serait donc utile d'étudier l'impact à plus long terme.

Notre deuxième objectif était de déterminer si le résultat sur le quotient plantaire nous permettait d'observer un effet spécifique de l'intégration des semelles sur la marche et la posture statique. Pour rappel, nous avons sélectionné trois sous-populations dans la première étude pour nous assurer que leurs quotients plantaires ne se chevauchaient pas. Le calcul du nouveau quotient plantaire ne donne pas la même distribution des participants. Nous ne trouvons plus trois sous-

groupes, mais nous avons plutôt une distribution continue. Ce quotient ne semble pas être stable dans le temps. Cependant, nous devons préciser que les deux études ne se sont pas déroulées à la même période. Il est possible que des facteurs intrinsèques de l'individu aient influencé sa réponse. Bien que les critères d'inclusion étaient les mêmes, nous n'avons cependant pas contrôlé le facteur cognitif. La réalisation de l'expérience en laboratoire peut être plus contraignante en raison de la configuration de capture du mouvement, des vêtements spécifiques requis, ou de la présence des trois individus (souvent inconnus) pour la collecte des données. L'utilisation du quotient en milieu clinique semble prématurée. Les facteurs environnementaux et intrinsèques des sujets sains semblent influencer les réponses. Il est donc difficile de suivre les individus au fil du temps en utilisant ce critère. La question de la temporalité est importante, tant en ce qui concerne l'intégration du composant de la semelle que le suivi des patients. D'autres recherches sont nécessaires pour mieux comprendre tous les facteurs qui modifient la réponse du quotient plantaire. De même, l'évaluation de la capacité d'intégration plantaire peut se faire en réduisant l'information à l'aide d'inserts en mousse. Sur la base des résultats de cette étude et de la littérature existante, il pourrait être possible de stimuler le système à des fins d'évaluation. Que ce soit un relief ovoïde lisse ou des matériaux texturés, ils semblent induire des réponses tant dans le contrôle statique que dynamique. Il pourrait être intéressant de considérer ce quotient avec un matériau texturé, par exemple. On sait que l'interposition de tels matériaux réduit les oscillations individuelles. En effet, cette stimulation presque constante active le système de contrôle moteur et permet une alerte continue du système d'équilibre. Considérer un PQ "stimulé" plutôt qu' "inhibé" pourrait fournir de nouvelles perspectives sur la qualité de l'intégration.

En fin de compte, il existe de multiples paramètres du centre de pression (CoP) qui reflètent un déséquilibre statique. Il est nécessaire de tenir compte de l'évaluation de plusieurs paramètres du contrôle statique pour obtenir une vue plus détaillée de celui de nos patients.

Conclusion

L'objectif de ce travail était de normaliser et d'évaluer les pratiques cliniques en podologie. Nos résultats démontrent un impact significatif du contexte de mesure. Ce point initial est particulièrement important. En effet, le manque de normalisation dans les emplacements de mesure entraîne des réponses différentes du même patient. Par conséquent, il devient impossible de comparer ces résultats entre les professionnels. La normalisation au sein de notre propre pratique clinique nous permettra de comparer le patient au fil du temps. Cela contribuera à réduire les résultats biaisés. L'utilisation du PQ devrait être mesurée et combinée à d'autres tests pour mettre en évidence un éventuel déficit d'intégration plantaire. Nous ne trouvons pas de lien entre ce quotient et l'intégration des composants de la semelle. Ces résultats diffèrent de la littérature et nécessitent des recherches supplémentaires pour les expliquer. Bien que cela soit un défi dans la routine clinique, l'analyse de la trajectoire locomotrice semble être précieuse pour évaluer l'intégration sensorielle des semelles orthopédiques. Des ajustements dans les pratiques et les matériaux peuvent être nécessaires à envisager. Cela fournirait aux professionnels un nouvel outil d'évaluation.

Ce travail contribue à la connaissance dans le domaine de la podologie. Des recherches supplémentaires sont nécessaires pour approfondir notre compréhension. Ces résultats devraient être intégrés dans une pratique basée sur des preuves, en tenant compte à la fois des considérations du patient et des données cliniques.

Enfin, les tests réalisés et la recherche devraient viser la validité écologique autant que possible, en reflétant au mieux la réalité quotidienne. Cette dimension semble essentielle pour des soins optimaux aux patients. Évaluer une situation non écologique et baser les décisions thérapeutiques dessus peut certainement conduire à des applications cliniques qui ne sont pas adaptées. À cet égard, l'analyse de la démarche dans les cliniques de podologie semble essentielle. L'analyse instrumentée fournit des données plus précises. Cependant, les outils de laboratoire utilisés dans cette étude ne sont pas facilement transférables en milieu clinique. La diffusion d'outils cliniques pour de telles évaluations serait un ajout précieux pour les professionnels, leur permettant d'améliorer leur analyse et de croiser plus efficacement les informations.

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Titre : Normalisation et évaluation des pratiques cliniques en podologie : Contrôle postural et locomotion

Mots clés : podologie, control postural, locomotion, semelles, quotient plantaire

Résumé : L'évaluation des capacités posturales et motrices d'un individu sont essentielles pour une prise en soin en podologie. Ce travail a pour premier objectif de standardiser et d'évaluer l'utilisation du quotient plantaire dans la pratique clinique. Sa mesure sur plateforme de force permet de quantifier la capacité du sujet à maintenir une posture statique lors d'une perturbation podale (usuellement une plaque de mousse). L'objectif est en premier lieu de comprendre quels conditions extrinsèques modifient la réponse (choix de la mousse, environnement visuel avec présence de cible ou distance du mur). Les résultats mettent en évidence un effet important de la vision sur le quotient plantaire avec un effet de la distance du mur et du type de cible présentée (une cible texturée permet un meilleur stabilité qu'une cible simple ou qu'une absence de cible).

Dans un second temps, l'analyse porte sur son utilisation dans le domaine clinique. Il s'agit d'évaluer si le résultat obtenu au quotient plantaire permet de déterminer la capacité d'un individu à intégrer une semelle orthopédique. Pour cela, une analyse statique et sur la marche des sujets avec port de semelles orthopédiques est réalisé. Le résultat montre une modification non orientée de l'équilibre statique et dynamique avec les semelles. L'analyse de la marche montre une diminution de l'écart entre le positionnement des pas et la projection du centre de masse. Ces résultats ne permettent pas un transfert dans le champ clinique. D'autres analyses sont nécessaires pour comprendre le mécanisme d'action de ces semelles afin de les proposer à la bonne population de patients.

Title : Standardizing and evaluating clinical practices in Podiatry: Postural control and Gait

Keywords : Podiatry, postural control, Gait, Foot orthoses, plantar quotient

Abstract : The assessment of an individual's postural and motor capabilities is crucial for podiatric care. This work aims to first standardize and evaluate the use of the plantar quotient in clinical practice. Its measurement on a force platform allows quantifying an individual's ability to maintain a static balance during a podal disturbance (typically a foam pad). The primary objective is to understand which extrinsic conditions modify the response (choice of foam, visual environment with the presence of a target or distance from the wall). The results highlight a significant effect of vision on the plantar quotient, with an impact of the distance from the wall and the type of presented target (textured target provides better stability than a simple target or no target).

In the second phase, the analysis focuses on its application in the clinical field. The goal is to assess whether the plantar quotient result can determine an individual's ability to integrate foot orthosis. To achieve this, a static and walking analysis of subjects wearing foot orthosis is conducted. The results show an unoriented modification of static balance with the insoles (Centre of pressure displacement is rising up with foot orthoses translating a challenged static balance). Gait analysis showed a reduction in the gap between step positioning and center-of-mass projection. These results cannot be transferred to the clinical field. Further analysis is needed to understand the mechanism of action of these insoles, so that they can be offered to the right patient population.