

EVOLUTION, APPLICATIONS AND FUTURE POTENTIAL OF HUMAN BALANCE MEASUREMENT

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Abstract

In this review, we intend to provide a definition of human balance, give an overview of the history of human balance measurement methods and tools used, the different areas of application (e.g. rehabilitation, senior care, sports applications, etc.) and future possibilities.

The earliest historical mention of measuring human balance for medical purposes is surprisingly late compared to other physiological examinations. While balance as a concept has ancient roots – appearing in Egyptian mythology and Roman symbolism – the scientific and medical measurement of posture control began with Romberg in the 19th century and only became widespread in the mid-20th century. The dynamic development of force plate technology, which has accelerated significantly in recent decades and continues to do so today, has had a significant impact on the understanding of the mechanisms of human movement and balance in a wide variety of research areas, from clinical rehabilitation to sports applications and sleep quality. By collecting accurate and meaningful data on human balance parameters such as center of pressure (COP), plantar pressure distribution (PPD) and

torque patterns, force plates allow the measurement and detailed analysis of movement dynamics and balance characteristics. Integration of force plate systems into a virtual reality environment has been implemented in order to develop different personalized, user-friendly rehabilitation environments for patients recovering from various injuries (e.g. stroke) or following medical interventions (e.g. surgeries). In addition, advances in machine learning and artificial intelligence are enabling the development of sophisticated algorithms to analyze data gained from force plate measurement systems.

Keywords: human balance, postural stability, stabilometry evolution, force plate

1. Introduction

Maintenance and control of human balance are one of the most complex and coordinated functions, which is ensured jointly by the nervous system, sensory organs, muscles, and human biomechanical structures. Balance is not merely the ability to maintain a stable spatial position of the body, but rather a dynamic process of adaptation during which a person is able to respond to external and internal environmental changes, thereby maintaining functional integrity and mobility (Horak, 2006). The study of balance therefore plays a key role not only in basic research, but also in clinical diagnostics, rehabilitation, sports science, and cognitive neuroscience (Shumway-Cook, 2017; Geurts, 1974). The purpose of this document is to provide a comprehensive and systematic overview of the theoretical, technological, and application aspects of determining and measuring human balance. (Mancini, 2010; Paillard, 2017; Maki, 1996; Redfern, 2001; Mousavi Hondori, 2014).

2. Definition of human balance measurement

Human balance measurement (or human balance testing) can be defined in several different ways, depending on whether it is approached from a medical, sports science, biomechanical, neurological or technology-device-based perspective. Here are some common definitions in different contexts:

2.1. General definition (Biomechanical Approach)

Human balance measurement is a test procedure that aims to objectively assess the static or dynamic stability of the human body using various sensory, motion analysis or posturographic methods.

Concept: The ability to maintain balance, i.e. to maintain the center of gravity (CoG) of the body within the support surface (Base of Support, BoS), whether in a static (e.g. standing) or dynamic (e.g. walking) position.

Key Actions

Static balance is the ability to maintain postural stability and orientation with the center of mass over the base of support and body at rest.

Dynamic balance: transitions between body positions stability in motion or movement; defining dynamic postural stability is more challenging. Dynamic balance is the ability to transfer the vertical projection of the center of gravity around the supporting base of support. Dynamic balance is the ability to maintain postural stability and orientation with the center of mass over the base of support while the body parts are in motion. (Physiopedia, 2013)

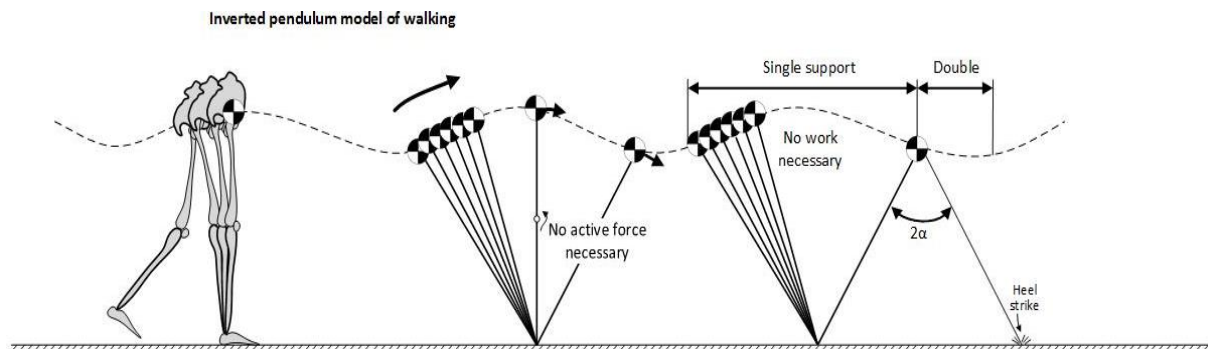


Figure 1. Inverted pendulum model of walking. (Kim, 2013)

The inverted pendulum model of gait biomechanics states that the body's center of mass (COM) moves across the leading leg as if rolling over a rigid, upside-down pendulum during the gait cycle. This model simplifies human walking: the role of the leading leg is similar to that of a rigid rod over which the COM describes an arc, while an efficient exchange of potential and kinetic energy takes place, resulting in energy-efficient walking.

This model is widely used for biomechanical analysis of gait, as well as in robotics and humanoid gait simulations, as it provides a simplified dynamic description of COM motion.

Note: The model is not necessarily an accurate physical representation of human gait, but it provides a very useful simplified dynamic representation of COM motion and GRF profiles.

2.2. Medical definition (in a Neurological-Physiological Context)

Human balance measurement is the study of the interaction of balance functions, i.e. the visual, vestibular and somatosensory systems, to diagnose possible neurological or inner ear imbalances.

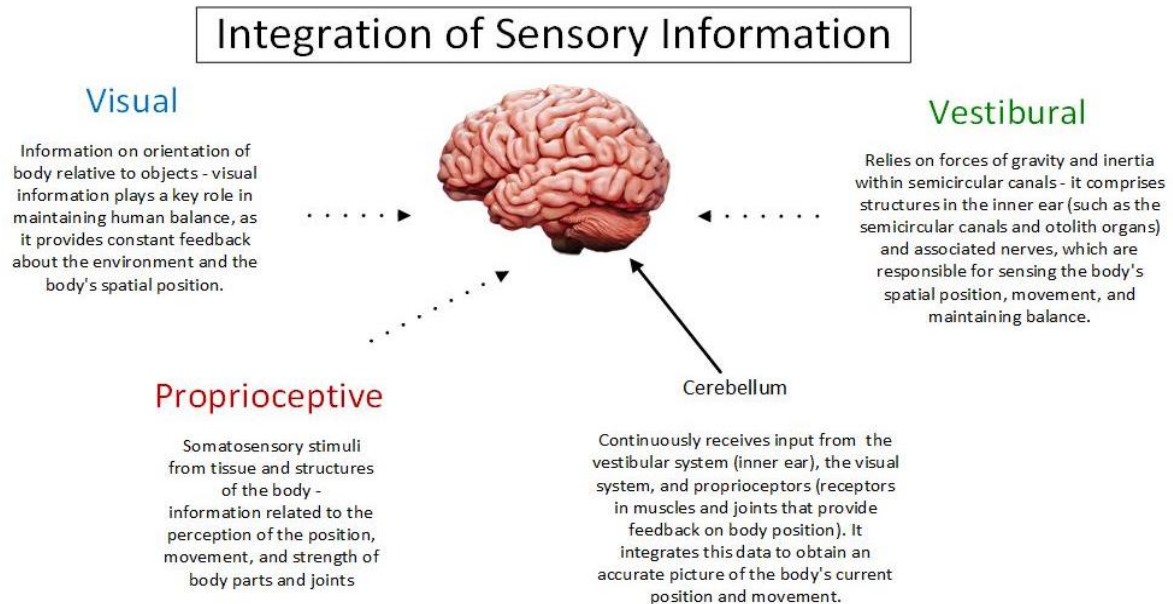


Figure 2. Integration of sensory information.

Concept: Balance is based on the interplay of the visual, vestibular, and proprioceptive systems. The study of imbalances is based on the separation of the functioning of these systems.

Key Tests: Romberg test: eyes closed to maintain balance; positive test indicates proprioceptive deficit; Sharpened Romberg: version performed on a narrower support surface.

2.3. Sports science definition

Balance measurement is a quantified test of the stability abilities of athletes to determine the effectiveness of keeping the body in balance in various movement situations.

Concept: Quantitative assessment of athletes' ability to balance in a variety of movement situations to optimize performance and prevent injury.

Areas of Focus:

- Limits of Stability: the limit of the CoG (Center of Gravity) without falling
- Functional Reach Test, Four-Square Step Test, Unipedal Stance Test (unipedalizm)

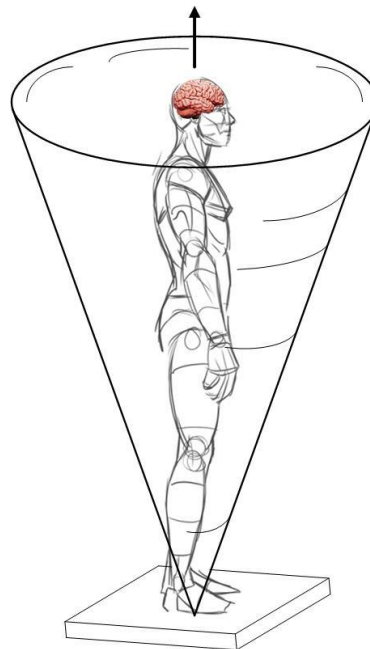


Figure 3. Maintaining balance as an inverted cone.

The term inverted cone is used in the biomechanical study of body balance to describe a visual model in which the relationship between the body's center of gravity and the contact surface (ground surface, area under the feet) determines how stable an individual is. This inverted cone delimits the spatial path traveled by the rod of the inverted pendulum. A simple concept:

- BOS (Base of Support) = the area on which the body rests (e.g., the contours of both feet).
- COG/COM (Center of Gravity/Center of Mass) = the body's center of gravity.
- In order for the body to be balanced, the projection of the COG must fall on the ground within the BOS. If it slips out of the BOS, the body becomes unstable and "falls."

The inverted cone approach depicts this as if the body formed an upward-widening cone with its apex on the ground (in the center of the support zone), the extent of which shows how much space the

COM fluctuation occupies even in a stable position. The wider this "cone", the greater the stability — that is, the body is able to move the COM to a greater extent without falling out of the BOS.

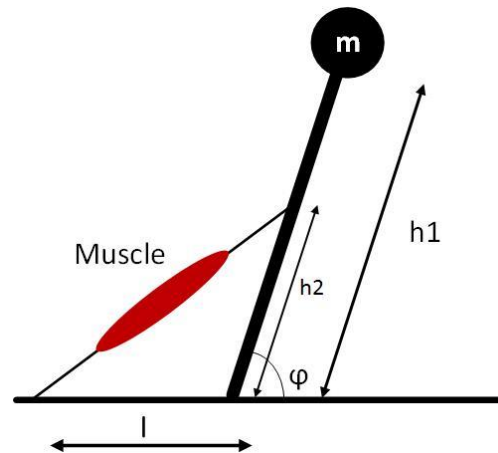


Figure 4. Schematic diagram of the joint involved in maintaining balance. (Sarmadi, 2017)

The main topic of the study is the biomechanical and neuromuscular regulation of body balance, in particular the role of proprioceptive perception and joint feedback in maintaining static and dynamic balance. Maintaining balance requires not only data from the eyes (visual system) and inner ear (vestibular system), but also proprioception from the muscles and joints, which continuously send information to the central nervous system about the position of the limbs and joint angles.

For this reason, studies often produce schematic diagrams showing how different joints (e.g., ankle, knee, hip) are involved in maintaining body balance and how these proprioceptive signals are integrated to maintain stability.

Explanation of symbols:

"l": The length between the joint pivot point and the center of mass (COM).

" φ " (phi): The angle of deviation of the pendulum (body segment) from the vertical.

" h_1 ": height of the lower segment (e.g., ankle–hip or ankle–COM)

" h_2 ": height of the upper segment or total COM from the ground

2.4. Functional definition (Rehabilitation purposes)

The aim of human balance assessment is to evaluate postural and locomotor control functions during daily activities, with a particular focus on fall risk, safety of movement, and monitoring rehabilitation progress.

Concept: The aim of the balance test is to assess the safe performance of everyday functions, including the effectiveness of fall prevention and rehabilitation.

Common measurement and testing procedures:

- Berg Balance Scale (BBS): 14 tasks, 0-56 points; ≤ 45 points = risk of falling
- Tinetti Test (Performance-Oriented Mobility Assessment Performance-Oriented Mobility Assessment, POMA): static balance + formal assessment of gait
- Timed Up and Go (TUG): stand up - 3 m walk - sit back down; > 20 sec fall risk
- Balance Evaluation Systems Test (BESTest) / Mini-BESTest: comprehensive test for several balance components - e.g. anticipatory, automatic, sensory.

- Hierarchical Assessment of Balance and Mobility (HABAM): in-patient mobility assessment in hospitals. (Hierarchical Assessment of Balance and Mobility, 2025)

2.5. Technology/Device-Based Approach

Concept: advanced technologies - such as portable IMU (Inertial Measurement Unit) sensors, force plates, motion and video analytics systems - enable real-time, accurate data collection in both laboratory and home environments.

Benefits: objective, quantitative data, easy to carry, easy to use, their emergence opens up the possibility of machine learning-based data processing, and makes it possible to demonstrate the relationship between other characteristics and parameters (e.g., mental fatigue).

2.6. Summary of definitions of Human Balance Measurement

2.6.1. Definition summary table

Table 1. Definition summary

Approach	Concept	Tests/Scales	Main Objectives
Biomechanical	CoG & BoS	Force plate, IMU, MoCap	Measure Stability
Medical / Neurological	Integration of Sensor Systems	Romberg, Sharpened Romberg	Diagnosis
Sports Sciences	Dinamic Balance	Limits of Stability, Four-Square Step, Unipedal Stance	Performance, Injury Protection
Functional / Rehabilitation	Daily Activity	BBS, Tinetti, TUG, BESTest, HABAM	Function, Fall Risk
Technology / Device-Based	Sensor Data Analysis	IMUs, Force Plate, Activity Analises	Objective, High accuracy

3. A Brief history of weight and balance measurement

3.1. History of weight measurement

The importance of measuring human balance was recognized quite late, in the 19th century, and began to be applied in medicine by Romberg. The concept of mental and physical balance, however, was already known in ancient times, although no measurement method was applied to it. However, the application of equilibrium was known, especially in scales. We shall therefore begin our overview with a presentation of the development of scales.

Mesopotamia, Egypt (~5000-2000 BC): as early as ancient Greece and Egypt (around 5000 BC), there were two-armed scales used by traders to measure goods. Egyptians used the “deben” unit (approx. 91 g) - several models of which have survived. Indus Valley (~2000 BC): regular cubic stones on one side of the scales, weights on the other side, often very accurate. Indus Valley Civilization used standardized cubic stone weights as part of a sophisticated system of measurement. China, Rome, Greece (3rd-1st century BC): bronze masses, steelyards appeared; Archimedes had already proposed

hydrostatic scales for the examination of gold crowns, which became famous. It is considered that the scales originated in ancient Egypt.

3.1.1. Middle ages and modern times

Auncel (England, 14th c.): The auncel was an unbalanced scale used in England. The goods were hung on the shorter end of the rod and the weight was pushed until the balance was set. Roberval scale (1669): Gilles Personne de Roberval created a new layout of scales that is not sensitive to location. Quintenz (decimal balance 1821): Quintenz-Dezimalwaage (also known as Quintenz balance) is a historical type of balance with asymmetrical arms (1:10), developed by Friedrich Alois Quintenz (1774-1822), a German (Alsatian) monk and mathematics professor in Strasbourg, France, patented in 1821 and on the market in 1822. Between 1822 and 1827, Jean-Baptiste Schwilgué and Frédéric Rollé refined the invention, developed it further and produced it on a large scale.

3.1.2. Specialization and mechanical innovations

Leonardo da Vinci made two designs, one triangular and the other semicircular, but they both worked on the same principle. The object to be measured was placed in a suspended pan. The chart acts as a pendulum and finds a new balance position. The weight is represented on the chart by a plum bob crossing its surface. Like many of Leonardo's ideas, including the autogyro, this scale was ahead of its time and was not completed until three hundred years after his death. During Leonardo's lifetime, a further improvement in the accuracy of the balance, still in use today, occurred - the development of the Swan Neck Beam, so named because of its shape. Knife-edges were cut into the ends of the swan neck perpendicular to the beam. (Jenemann, 1999)

Spring scales - A more accurate method of measurement only emerged at the end of the 17th century, when the Industrial Revolution brought major technological advances. After the invention of the spring balance by British balance maker Richard Salter around 1770, the balance no longer relied on counterweights.

Mass Standards and Regularization

Pound and ounce systems (e.g. libra) were developed in the Hellenic-Roman period (~100 BC), then standardized in the Middle Ages, and later became part of the Imperial system.

Metric system and international standards: working papers and the introduction of the prototype kilogram, replaced in 2019 by a physical definition of the kilogram based on the Planck constant.

3.1.3. Precision and digital evolution

Precision Balances (macro / microbalance): The very first precision balance was most likely developed and built by British watchmaker John Harrison in the early 1770s. State-of-the-art precision balances, known in scientific laboratories as macro balances, are sensitive enough to weigh up to 200 grams with an accuracy of 0.1 milligram. More sensitive balances are the microbalances, which are able to weigh up to 0.1 grams of load to an accuracy of 3.53 parts per 1 millionth of a gram.

- Torsion balance, Loránd Eötvös (1902): microgram precision.
- Electronic digital scales: from the mid-20th century, with digital display, IoT (Internet of Things) functions.

3.2. History of balance measurement

3.2.1. Antique beginnings

The Egyptians and Greeks had an excellent understanding of the principles of body balance, which they used in their building projects, in the design of their scales and in their healing practices. Hippocrates and Galenos were already concerned with the regularity of posture and movement in the 5th-2nd centuries BC, which indirectly meant observing balance. At the same time, the concept of static equilibrium (e.g. the principle of lever balances) was also being developed.

- Archimedes (287-212 BC): uses hydrostatic scales to prove the mass ratio (e.g. King Hiero's crown).
- Greeks, Romans: early knowledge of the mechanical principles of balance; introduction of the Roman "knife-edge" bearing improved accuracy.

3.2.2. Middle ages and renaissance - Philosophy and observation

Despite the stagnation of medicine in the Middle Ages, the theory of equilibrium lived on in philosophy and the arts. Harmony of body and soul, as an inner "state of equilibrium", remained a fundamental principle of medicine.

3.2.3. Neurology a science in its own right

Moritz Heinrich Romberg (1795-1873): German neurologist who was one of the most prominent figures in the early development of neuroscience in the 19th century.

His pioneering work played a significant role in the development of neurology as a distinct medical specialty. His most famous work is the *Lehrbuch der Nervenkrankheiten des Menschen* (Textbook of Human Nervous Diseases), published between 1840 and 1846, in which he described in detail, among other things, the syphilitic nervous complication tabes dorsalis. (Dunea, 2017)

He also made a major contribution to the translation of the neurological works of Charles Bell and Andrew Marshal into German (1830-1832), which greatly shaped the development of German neurology.

Scientific Heritage

- A pioneer in neurology: widely recognized as the founder of a new, distinct neuroscience - also known as the "first clinical neurologist"; one of the first physicians to systematically observe and document neurological diseases clinically.
- Romberg's sign: defined by the discovery of the earliest characteristic neurological signs of tabes dorsalis: loss of balance with eyes closed - indicating damage to the proprioceptive pathway. (Kagan, 2007)
- Education and clinical methodology: strongly advocated the emphasis on pathological and physical examinations in diagnosis; pioneered instrument-free, visual neurological examinations.
- Romberg test: it is a neurological test method used to examine proprioception (the perception of the body's position); the aim of the test is to determine whether the patient can maintain balance when visual cues are excluded.

Impact on Neurology Today

- His studies made neurology a science in its own right.
- His work has remained a basic work for centuries: his textbook has gone through several editions and language translations.

- The tests and reflexes he defined are still part of everyday routine, used all over the world.

3.2.4. 20th Century - Technological breakthroughs and technical innovations

Force Platform (20th-21st century): works with load cells, analyses pressure points, center of gravity movements - from labs to home Wii Balance Board (2007). Force platform is called a "whole-body accelerometer"; its output is the acceleration of the whole body's center of gravity in three-dimensional space, including the limb on the ground and the leg swinging in the air. (Bonde-Petersen, 1975)

3-axis Force Plate Coordinate System

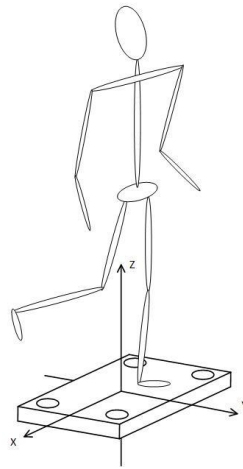


Figure 5. One of the advanced tools for measuring balance is the force plate.

Stabilometric Systems: are based on a flat, sensitive surface with force sensors underneath. These sensors are able to register the pressure exerted by the body at different points on the platform, and from this it is possible to determine the position of the body center of gravity and its displacement over time. Measured data are evaluated by computer software that displays the trajectory of the CoP, calculating its speed, area, and other characteristics.

Key Measuring Parameters: CoP (Centre of Pressure) trajectory - the projection of the body's center of gravity onto the platform plane, changing over time. Swaying amplitude - the rate at which the body sways; the amount of sway of the body (especially the torso or head) when balancing, for example when standing still or trying to remain stable while moving. This sway can happen forward-backward (antero-posterior), left-right (medio-lateral).

Stability index - numerical values describing the ability to maintain equilibrium: medio-lateral stability index (MLSI) represents fluctuations from the horizontal around the mediolateral axis; anterior-posterior stability index (APSI) represents fluctuations from the horizontal around the anteroposterior axis; overall stability index (OSI) a composite of MLSI and APSI so it is sensitive to changes in both directions.

Roll Rate - in the context of Center of Pressure (CoP); it refers to the speed and direction of the CoP's movement over time, specifically the rate of change in the CoP's position in the medial-lateral (side-to-side) direction. It essentially quantifies how quickly and in what direction the body is shifting its weight laterally.

Symmetry Index (SI) – this is a way to quantify the symmetry or asymmetry of a variable measured on both sides of the body, such as in gait analysis. It's often expressed as a ratio or percentage, comparing the values obtained from the right and left sides. A symmetry index of 0% typically indicates perfect symmetry, while values further from 0 suggest increasing asymmetry.

Inertial Measurement Unit (IMU) and portable sensors allow precise assessment of the body's balance in different positions (standing, walking). An IMU is an electronic device that uses a combination of accelerometers, gyroscopes, and sometimes magnetometers to measure and report the specific force, angular velocity, and sometimes the magnetic field of the body.

3.2.5. The 21st century: Digital age and portable systems

The proliferation of wearable sensors, smart devices, and virtual reality technologies has revolutionized balance testing and training. Accelerometers and gyroscopes in mobile phones can now be used to measure body stability at home. In addition, artificial intelligence and machine learning have enabled automated balance analyses, opening up new possibilities for diagnostics, rehabilitation, and optimization of sports performance.

4. State-Of-The-Art

4.1. Technological and professional status - Current level of development

4.1.1. Integration and recent directions

Human balance measuring instruments, such as force plates, play a role in standardization and the accurate recording of physical quantities. Metrological interconnection, in the context of measurement and instrumentation, refers to the establishment of a traceable and reliable connection between different measurement systems or devices, ensuring that they are all referencing the same standard and providing consistent results. It's about creating a consistent chain of calibrations that links individual measurements to a recognized reference, often at a national or international level.

Digital and automated balance measurement systems utilize electronic sensors and microprocessors to accurately and rapidly determine the mass of objects. They offer enhanced precision and reliability compared to traditional mechanical scales, often incorporating features like automatic calibration, data logging, and tare functions (setting a scale or balance to zero). These systems are crucial in various fields, including scientific research, manufacturing, and quality control, where precise weight measurements are essential.

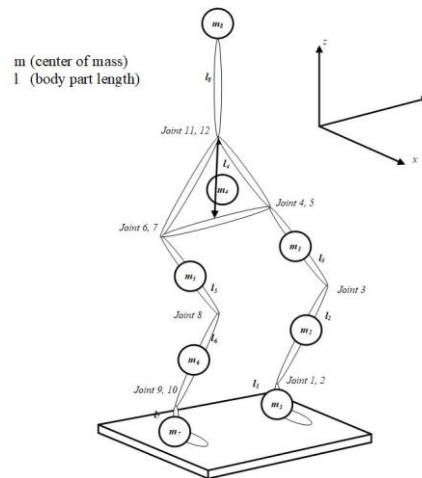


Figure 6. Body part lengths, joints, and centers of mass in the coordinate system of the inverted pendulum model.

Joints are considered as pivot points (hinges) in the model. In the simplest inverted pendulum model, the ankle joint is the pivot point. In multi-segment models, the knee and hip joints are also included. Each joint determines where the angular movement occurs in the coordinate system. The position of the joint serves as a reference point for calculating angles and torques.

4.1.2. Interdisciplinary areas

These areas integrate knowledge and methods from various fields to understand, assess, and improve human balance.

Biomedical Engineering: This field focuses on developing assistive devices and rehabilitation strategies for individuals with balance impairments. It draws on principles of biomechanics, human movement, and engineering to design and evaluate technologies like assistive robots, prosthetics, and balance training equipment.

Neurology/Neuroscience: Understanding the neurological processes underlying balance is crucial. Interdisciplinary research in this area combines neuroscience, neurophysiology, and clinical neurology to investigate the brain's role in maintaining balance, identifying neurological causes of balance disorders, and developing targeted interventions.

Geriatrics/Aging: Geriatric medicine, along with kinesiology and public health, collaborates to study age-related changes in balance, identify risk factors, and implement fall prevention strategies.

Sports Science: Kinesiology, biomechanics, and sports psychology work together to analyze movement patterns, optimize athletic performance, and reduce the risk of injuries.

Psychology: Factors like anxiety and fear can affect balance. Psychology, in conjunction with biomechanics and motor control, explores the relationship between psychological states and balance control, and investigates the effectiveness of psychological interventions for improving balance in various populations.

Public Health: Initiatives aim to reduce falls and injuries related to balance problems. This involves collaborating with healthcare professionals, policymakers, and community organizations to implement public awareness campaigns, develop fall prevention programs, and improve access to balance

assessment and rehabilitation services. In addition, it can also be used to estimate life expectancy. (Cooper, 2014)

Computer Science/Data Science: With advancements in technology, computer science and data science play an increasingly important role in balance measurement. This includes developing sophisticated algorithms for analyzing balance data, creating virtual reality environments for balance training, and using machine learning to predict falls and personalize interventions.

4.1.3. Measurement techniques

Virtual Reality and Haptic Feedback: VR-based systems are increasingly available for targeted balance training and diagnostics.

Integrating EEG and Neurophysiological Measurements: Advanced research is investigating the relationship between brain activity and balance control (e.g. motor cortex and cerebellum activity). (Chen, 2021)

4.1.4. Data Processing and Artificial Intelligence

Artificial intelligence and machine learning play a key role in the field of modern balance and movement analysis. With the help of machine learning models such as decision trees or neural networks, we are able to diagnose and predict balance disorders. Automated clustering and pattern recognition methods enable detailed analysis of posture and movement patterns, revealing hidden correlations. In addition, digitized, real-time biofeedback systems provide immediate feedback to users, supporting rehabilitation, sports performance improvement, or prevention, while data is continuously collected and learned by the systems. (Ui-jae Hwang, 2024)

Main features:

- Using machine learning models (e.g. decision trees, neural networks) to diagnose and predict imbalances;
- Automated clustering and pattern recognition based on posture and movement patterns;
- Digitized, real-time biofeedback systems.

4.2. Integration trends

Wearable devices such as smart shoes, IMU belts, and smart watches, which can collect data on body position and movement patterns in a mobile environment, are playing an increasingly important role in balance measurements and motion analysis (digital biomarkers). At the same time, telemetry and remote diagnostic solutions are evolving, enabling continuous monitoring of rehabilitation processes or elderly care at home or in remote locations. Such integrated systems ensure more accurate data collection and analyses, and also enable personalized interventions and immediate feedback.

Main features:

- Wearable devices: smart shoes, IMU belts, smart watches that can collect balance data in a mobile environment;
- Telemetry and remote diagnostics: remote monitoring solutions for rehabilitation and elderly care.

4.3. Main areas of application

4.3.1. Applications for medical diagnostics

Measuring human balance plays a key role in medical diagnostics and rehabilitation. It can be used to detect and monitor neurological diseases such as Parkinson's disease, multiple sclerosis, or post-stroke

conditions, thereby supporting targeted treatments and optimizing the rehabilitation process. It also enables the accurate diagnosis of vestibular (inner ear) disorders. Early detection of age-related balance disorders can form the basis for fall prevention programs, reducing the risk of injury and improving the quality of life for the elderly. Force plates, stabilometers, motion tracking systems, and VR-based training, provide accurate and objective data on posture, movement, and balance.

Main features:

- Detection and monitoring of neurological diseases: e.g. Parkinson's disease, multiple sclerosis, post-stroke rehabilitation; (Rebecca Cradini, 2025)
- Diagnosis of vestibular (inner ear) disorders; (Jeroen Venhovens, 2020)
- Early detection of age-related imbalance - the basis for fall prevention programmes. (Steve Bryson, 2025)

4.3.2. Rehabilitation and therapy

Developing balance skills plays a fundamental role in the rehabilitation of neurological and orthopedic patients. Targeted balance training helps to improve movement coordination, stability, and posture, reducing the risk of accidents and falls. Modern rehabilitation increasingly uses VR-based platforms, where gamified exercises support regular training in a motivating and enjoyable way. In addition, biofeedback devices can be used to implement targeted neurofeedback training, which provides real-time feedback to optimize body position and movement patterns. Together, these methods increase therapeutic effectiveness, accelerate recovery, and support patients' independence in everyday life. (De Natale, 2025)

Main features:

- Balance training for neurological and orthopedic patients,
- VR-based rehabilitation platforms with gamified exercises,
- Targeted neurofeedback using biofeedback devices.

4.3.3. Sport and performance diagnostics

Accurate measurement of balance, proprioception, and posture control plays a key role in optimizing athletic performance. This data allows for the assessment of sport-specific abilities, such as the stability and movement coordination of gymnasts or skiers. During recovery from injury, regular balance measurements help monitor regeneration, assess load capacity, and minimize the risks of overexertion. Sports-specific balance indices can be used to provide personalized feedback, supporting effective training, performance enhancement, and injury prevention. Modern measurement systems such as force plates, stabilometers, and motion tracking systems provide objective and detailed information about athletes' balance and postural abilities. (Han, 2015)

Main features:

- Measurement of stability, proprioception and postural control in athletes,
- Post-injury recovery monitoring, load capacity measurement,
- Balance indices tailored to sport specificities (e.g. gymnast, skier).
- Rapid diagnosis of micro strokes (Renato B dos Santos et al., 2023)

4.3.4. Occupational health and ergonomics

Monitoring balance and posture is key to workplace safety and health, especially for tasks where workers stand for long periods or operate moving vehicles. Continuous measurement allows for accurate tracking of physical exertion and reduces the risks associated with overexertion. In addition, regular analysis of balance and movement data helps to identify fatigue and loss of coordination early on, thereby reducing

the likelihood of workplace accidents and injuries. Modern ergonomic systems, such as wearable sensors and motion tracking devices, provide objective, real-time information about the condition of workers, supporting safe and efficient work. (Moshawarb, 2022)

Main features:

- Monitoring of balance load during work (e.g. standing, handling moving vehicles),
- Detection of signs of fatigue and loss of coordination.

4.3.5. Research and basic research

When examining human balance, research focuses primarily on understanding the mechanisms of sensorimotor integration and neural adaptation. An important area is mapping the effects of aging processes on the balance system, as age-related changes can increase the risk of falls and injuries. In addition, modern basic research also covers the development of machine learning-based balance models that enable the objective analysis of posture, movement patterns, and adaptive responses. These models help the scientific community to better understand the regulation of balanced movement and develop prevention and rehabilitation strategies. Sensors, wearable devices, and computer simulations together support detailed investigation of mechanisms and the development of measurement methods.

Main features:

- Study of sensorimotor integration and neural adaptation, (Yokhesh K. Tamilselvam, 2024)
- Effect of ageing processes on the balance system, (Yoshimura, 2020)
- Machine learning-based balance model development. (Pitsik et al., 2022)

In recent years, a number of epidemiological and clinical studies have shown that simple measures of physical performance (such as grip strength, chair rise speed, and time spent balancing) are significant predictors of mortality risk, particularly in older adults.

The relationship between the three main indicators and mortality:

Grip strength (handgrip strength): measures the muscle strength of the upper limb, which is generally a good indicator of the muscular strength of the whole body. Its association with mortality is that poorer grip strength is associated with a significantly higher risk of mortality and is also a particularly good predictor of mortality from cardiovascular disease, cancer and general functional decline. Reduced grip strength is already an indicator of increased risk in middle age.

Chair stand test: measures the functional capacity of the leg and lower limb and neuromuscular coordination. Type of test: e.g. "5 chair stand-up times" or "how many stand-ups in 30 seconds". Relation to mortality: slower or more difficult standing up is associated with a significantly higher risk of death. It may also indicate a loss of muscle mass (sarcopenia), general frailty (a state of lassitude) and mobility problems. **Time spent in balance (e.g. time spent standing on one leg):** measures postural control and the level of neuromuscular integration. Relationship to mortality: those who cannot stand on one leg for more than 10 seconds have been shown to have a 2-3 times higher risk of death. It may be a particularly sensitive marker for predicting neurodegenerative diseases, stroke or chronic imbalances.

Table 2. Relationship between the three main indicators and mortality (Cooper, 2014)

Measurement	Indication	Low Performance	Risk of Mortality
Grip Strength	Muscular strength, overall health	5kg decrease	↓ Grip strength → ↑ mortality; +11–16 % mortality
Chair stand-up speed	Functional capacity, lower limb strength	>15 s / very low 5 CST	Slower → ↑ mortality; HR 1.88-2.78; combined HR 4.7

Balancing (time)	Neuromuscular stability	<10 s	<10 sec → ↑↑ mortality; 2-3 times higher mortality
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Fitness-for-Duty Assessment

The purpose of the Fitness-for-Duty (FFD) assessment is to determine whether an employee is capable of performing his/her duties safely and effectively without endangering their own health and safety or that of others.

Key features of the Fitness-for-Duty Assessment:

Physical and mental fitness assessment: The assessment takes into account the employee's physical condition, mental health, and the specific requirements of the job.

Job analysis: The assessment requires a detailed analysis of the job in order to determine what tasks need to be performed and what requirements these place on the employee.

Legal background: In the United States, Fitness-for-Duty Assessments are regulated by the Americans with Disabilities Act (ADA), which stipulates that employers may not require medical examinations of employees prior to employment unless it is necessary for the job.

Areas of application: FFD assessments are used particularly in high-risk occupations such as pilots, truck drivers, chemical plant workers, and other safety-sensitive positions.

Assessment results: Based on the results of the assessment, the employee may be deemed "fit for work," "fit for work with certain restrictions," or "unfit for work." In the latter case, the employer must consider modifying the job or transferring the employee to another position.

The purpose of the FFD assessment is to ensure the safety of employees and the workplace community, while taking into account the health status of the employee and the requirements of the job. (Misra, Castro-Vasquez, & Keyes, 2024)

Functional Capacity Evaluations (FCE)

This test is a three- to four-hour testing process that provides a snapshot of what a person can do at the time. It looks at things like flexibility, strength, endurance, dynamic material handling, repetitive activities and consistency of effort. Basically, it assesses a person's capability to carry out tasks so the person's abilities can be matched to job demands.

Provides objective, detailed information about an individual's physical capabilities, and/or workplace injuries & illnesses,

- Determines when a worker is able to return to work after an injury,
- Determines whether a worker will be able to perform their duties at full capacity or if they will need to work in a reduced capacity (i.e. with limitations),
- Helps prevent re-injury or additional workplace injuries.

On-field Assessment (Immediate/Acute Evaluation) - Off-field Assessment

The terms "on-field assessment" and "off-field assessment" are primarily used in sports medicine and injury treatment, especially in cases of trauma, head injuries, or muscle and joint injuries.

On-field Assessment (Immediate / Acute Evaluation)

Timing: Immediate assessment of the injury on the field or at the workplace.

Objective: To quickly assess the severity of the injury and factors critical to vital functions and safety.

Focus:

- Assessment of condition (consciousness, breathing, bleeding),
- Functional examination (movement, pain, stability),

- Decision: immediate transport to hospital or need for further examination.

Characteristics: Fast, protocol-based, often based on visual and tactile methods.

Example: Immediate examination of an athlete on the field after a head injury to determine whether they can remain in the game or must be removed from the field immediately. (Michael Anacker, 2023)

Off-field Assessment

Timing: After the injury, but away from the field, e.g., in the locker room, medical room, or clinic.

Purpose: Detailed, comprehensive examination to accurately diagnose the injury and develop a treatment plan.

Focus:

- Physical examination (joint stability, muscles, nerves)
- Additional tests (X-ray, MRI, lab)
- Functional tests for the rehabilitation plan

Features: More detailed, time-consuming, allows for thorough documentation and determination of a long-term treatment strategy.

Example: Off-field examination of athletes, where the extent of ligament damage is assessed in detail and a rehabilitation plan is prepared.

4.3.6. Additional testing methods

- Single Leg Stance Test
- Tandem Stance / Heel-to-Toe Walk Test
- BESS Test (Balance Error Scoring System)
- Berg Balance Scale (BBS)
- Tinetti Test (POMA)
- Sport Concussion Assessment Tool 6 (SCAT6)

5. Human Balance Measurement – Publication Map

5.1. Technological breakdown (Based on PubMed + Scopus Aggregates)

The search criteria for these results were the names of technologies/methods.

Table 3. Breakdown of publications by technology

Technology / Method	Number of Publications (2000–2025)	Comment
Force platform / posturography / stabilometry	~4,000–5,000	Classic equipment, numerous clinical and sports items.
IMU / Accelerometer / Gyroscope / Smartphone	~2,000–2,500	Dynamic growth after 2010; validation and application studies.
Computerized Dynamic Posturography (CDP / SOT ¹)	~1,200–1,500	Clinical standard; several vestibular and military applications.
Pressure-sensitive insole / Plantar pressure	~800–1,000	Clinical orthopedics, rehabilitation, sports.
VR/AR, Motion capture, new sensor fusion solutions	~300–500	An emerging field, primarily in rehabilitation.

¹ Sensory Organization Test

5.2. Breakdown by application

Table 4. Breakdown of publications by application

Field of Application	Number of Publications (2000–2025)	Comment
Geriatrics / fall risk / prevention	≥3,000	Largest corpus; fall prevention, elderly population.
Vestibular disorders / Otoneurology	~1,200–1,500	CDP/SOT dominant; diagnostics and rehabilitation.
Neurology (Parkinson's, stroke, MS, etc.)	~1,500–1,800	Disease-specific balance patterns, rehabilitation.
Sports / concussion / performance	~800–1,000	IMU, Y-Balance, injury prevention.
Military / Aviation / mTBI ²	~300–500	Fitness, concussion, SOT norms.
Metabolic / Other clinical (e.g., diabetes, amputation, orthopedics)	~200–400	Smaller but growing corpus.
Rehabilitation tech + Machine learning	~300–500	Treatment of various diseases, prediction models.

5.3. Publication trends (General pattern)

- 2000–2010: mainly force plate + CDP, classic clinical studies.
- After 2010: rapid growth of IMU and wearable sensors.
- After 2015: sports and military applications, concussion monitoring.
- After 2020: ML + AI-based balance analysis, VR/AR rehab.
- 2022–2025: more than 400–500 new articles per year in PubMed alone on the subject of "IMU + balance."

6. Conclusion and future prospects

Force measurement platforms, piezoelectric and optical sensors, and inertial measurement devices allow for the exploration of fine details of postural control, while subjective measures such as functional balance tests and clinical scales play an important complementary role in the holistic assessment of patient status. Integrated sensory information processing, motor responses, and cognitive modulations are closely related, and that dysfunction in any component significantly affects stability. Mental fatigue, cognitive load, and psychological factors such as attention and stress can significantly alter balance performance, which is particularly relevant in everyday life, sports, and rehabilitation. At the same time, pathological conditions such as neurological diseases or musculoskeletal injuries directly affect independent movement and functionality through balance disorders, which requires the development of measurable parameters and rehabilitation protocols in clinical practice.

In the field of sports and physical activity, measuring and improving balance plays a key role in optimizing performance, preventing injuries, and improving coordination. In addition, age-related changes and the decline in stability that occurs with aging are particularly important in terms of

² Mild Traumatic Brain Injury (mTBI)

prevention and maintaining mobility. State-of-the-art technologies such as wearable sensors, virtual and augmented reality-based measurement systems, and artificial intelligence-supported data analysis enable balance tests to deliver more accurate, faster, and more widely applicable results in both clinical and research environments.

Overall, it is pointed out that the examination and assessment of human balance is not merely an engineering or medical issue, but a key area in terms of quality of life, prevention, rehabilitation, and performance improvement. The combination of a multidisciplinary approach and innovative measurement methods will enable future research and applications to further deepen our systematic, comprehensive understanding of human balance, thereby promoting both practical and scientific progress.

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