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Handbook of balance and jump performance analysis using Inertial Measurement Units

Application in Volleyball Athletes for Performance Assessment and Injury Risk Monitoring

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Analysis of Static Balance

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1. ANALYSIS OF STATIC BALANCE

1.1. Rationale: why do we need to measure balance in volleyball players?

Balance measurements in volleyball players offer significant advantages for both performance enhancement and injury prevention. A strong sense of balance, encompassing both static and dynamic stability, is crucial for executing complex volleyball actions like jumping, landing, spiking, blocking, setting, and receiving. By assessing balance, coaches can identify deficits and tailor training programs to improve postural control, which directly translates to more efficient movement patterns, greater power generation during jumps, and enhanced agility for quick directional changes on the court. Furthermore, higher effectiveness of the postural control system is associated with a reduced risk of non-contact lower limb injuries, particularly ankle sprains, which are prevalent in volleyball due to the repetitive jumping and landing demands. Therefore, incorporating balance measurements and targeted balance training can lead to improved overall athletic performance and a healthier playing career for volleyball athletes.

Assessing balance in young athletes during childhood and adolescence is crucial for several interconnected reasons, impacting both their athletic development and long-term health. Firstly, balance is a foundational motor skill that underpins almost all physical activities, from everyday tasks like walking and running to complex sports movements. As children and adolescents mature, their balance control systems are still developing, with significant improvements occurring up to late adolescence. Regular balance assessments allow coaches and parents to monitor this development, identify any deficits or asymmetries, and tailor age-appropriate training interventions to foster optimal motor control and coordination.

1.2. Instrumental assessment of static balance

Even among top-level clubs and national teams, field-based methods for balance assessment are still widely used, as they offer practical, accessible, and cost-effective ways to evaluate stability in various sporting environments. Common examples include the Star Excursion Balance Test (SEBT) and its modified version, the Y-Balance Test (YBT), which assess balance by requiring athletes to maintain single-leg stance while reaching with the contralateral limb in various directions. Another widely used test is the Balance Error Scoring System (BESS), which objectively quantifies static postural stability by counting errors across different stance positions on both firm and foam surfaces with

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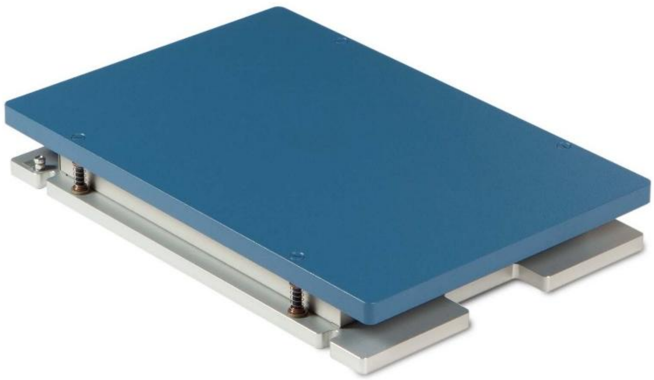
eyes closed. However, while these approaches are invaluable for identifying balance deficits, monitoring rehabilitation progress, and screening athletes for increased risk of lower extremity injuries, they often lack of accurate quantitative data that would be of superior quality to develop training and injury prevention strategies.

For such reasons, in recent times the use of instrumental techniques, in particular those which exploit the capabilities of force plates and Inertial Measurement Units (IMU) received increasing interest.

Force plates (also known as force platforms) are sophisticated measuring instruments designed to quantify the ground reaction forces (GRFs) exerted by a body standing on or moving across them. Think of them as highly sensitive scales that can measure not just your weight, but also the forces you apply in different directions (vertical, horizontal, and lateral) and how these forces change over time. They typically contain multiple sensors (such as strain gauges or piezoelectric sensors) that detect minute strains when force is applied, converting the effect associated with the application of mechanical forces into measurable electrical signals.



A force platform

For balance assessment in athletes, force plates provide highly objective and precise data that cannot be captured by the naked eye or simpler field tests. Here's how they are used: Force plates (also known as force platforms) are sophisticated measuring instruments designed to quantify the ground reaction forces (GRFs) exerted by a body standing on or moving across them. Think of them as highly sensitive scales that can measure not just your weight, but also the forces you apply in different directions (vertical, horizontal, and lateral) and how these forces change over time. They typically contain multiple sensors (such as strain gauges or piezoelectric sensors) that detect minute distortions when force is applied, converting these mechanical forces into measurable electrical signals.

For balance assessment in athletes, force plates provide highly objective and precise data that cannot be captured by the naked eye or simpler field tests. Here's how they are used:

- **Static Balance (Postural Sway):** Athletes stand still on the force plate(s) for a set period (e.g., 30-60 seconds), often in various stances (e.g., two-feet, single-leg, eyes open/closed). The force plate records the continuous fluctuations of the **Center of Pressure (COP)**, which is the point where the GRF acts on the support surface. Analysis of COP metrics—such as total excursion (the distance the COP travels), mean velocity (the average speed of COP movement), and ellipse area (the 95% confidence ellipse area enclosed by the COP trajectory)—provides insights into how much an athlete sways and how efficiently they control their posture. Smaller values generally indicate better static balance.

- **Dynamic Balance:** Force plates can also assess dynamic balance during movements like jumping, landing, or performing specific agility drills. For example, during a jump, they can measure the forces generated during the push-off and the forces experienced during landing. By analyzing the force-time curves, parameters like peak force, rate of force development (RFD), and impulse can be derived. In a landing task, a force plate can quantify how well an athlete absorbs impact, providing insights into their stability and control during dynamic movements crucial for injury prevention.

- **Asymmetry Detection:** With dual force plate systems (where two separate plates measure each limb independently), practitioners can identify asymmetries in force production or balance control between the left and right limbs. This is particularly valuable for athletes recovering from unilateral injuries, as it helps determine if symmetrical loading and stability have been regained before returning to sport.

- **Objective and Quantitative Data:** The primary advantage of force plates is their ability to provide objective, quantitative data on balance. This allows for precise

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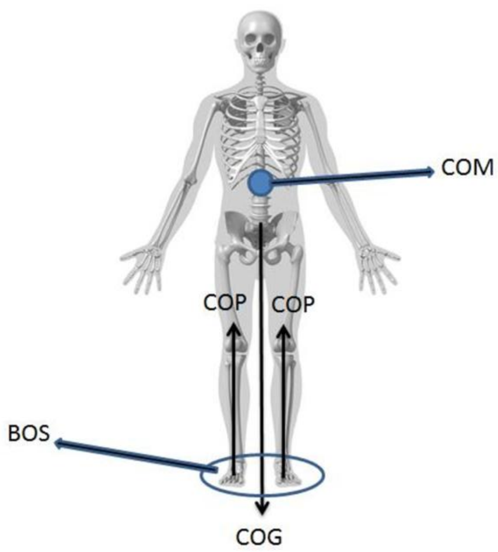
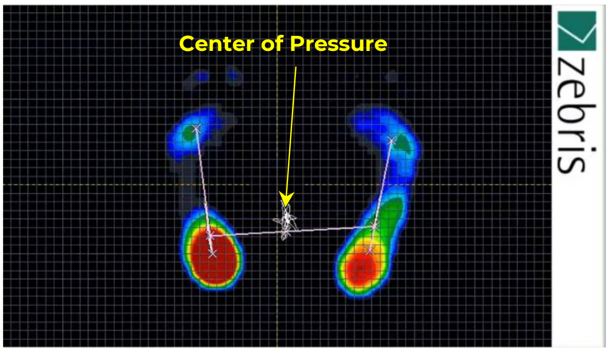
monitoring of changes over time (e.g., during rehabilitation or training cycles), identification of subtle balance deficits that might not be visible clinically, and the development of highly individualized training programs. While expensive and typically confined to laboratory or specialized clinic settings, force plates are considered the "gold standard" for detailed balance and movement analysis in sports science and rehabilitation.

	
Key variables of the postural control: COM:center of mass, COG: center of gravity (vertical projection of the COM to the ground), COP; center of pressure	*Center of Pressure is located between our feet. Its position continuously changes during a quiet upright stance*

1.3. A focus on postural sway analysis

Postural sway refers to the constant, small, and unconscious oscillations or movements your body makes to maintain an upright position while standing. Even when you believe you are standing perfectly still, your body is continuously making tiny adjustments to keep your center of gravity (that is, the verticla projection to the ground of your Center of Mass, COM) within your base of support and prevent you from falling over. This subtle movement is a dynamic process involving the complex interplay of sensory information (from your visual system, inner ear's vestibular system, and proprioceptors in your joints and muscles) and motor responses from your central nervous system

The quantitative analysis of postural sway is crucial for several reasons:

- **Objective Quantification of Stability**: Postural sway provides a quantifiable and objective measure of static balance. While an observer might subjectively notice someone "swaying," force plates and other sensors can precisely measure the amplitude (how much you sway), velocity (how fast you sway), and area of the body's COP movement. These metrics are direct indicators of how effectively an individual is controlling their posture

- **Sensitivity to Balance Deficits**: Increased postural sway often indicates reduced balance control. This can be due to various factors, including fatigue, injury (e.g., concussion, ankle sprain), or more serious neurological conditions. By measuring sway, clinicians and researchers can detect subtle impairments that might not be apparent during a quick visual assessment.

- **Identification of Sensory Reliance**: By altering sensory input (e.g., having an athlete stand with eyes closed or on an unstable surface), changes in postural sway can reveal which sensory systems an individual relies on most heavily for balance. For instance, increased sway with eyes closed suggests a greater reliance on visual input for balance control. This helps in targeting specific training or rehabilitation strategies.

- **Monitoring Progress and Risk**: Tracking changes in postural sway over time can be crucial for monitoring rehabilitation progress after an injury or for evaluating the effectiveness of balance training programs. Significant increases in sway may also serve as a predictive biomarker for an increased risk of falls, particularly in older adults or individuals with certain conditions

In essence, postural sway is not just a side effect of standing; it's a window into the efficiency and robustness of an individual's balance control system, making it a fundamental parameter in comprehensive balance assessments.

1.4. Yes, but in practice? How do we measure postural sway in laboratory and what parameters can I get from a sway analysis?

Measuring postural sway using a force plate involves a standardized protocol to ensure reliable and comparable data. Here's a typical procedure:

1) **Preparation of the Force Plate and Environment:**

The force plate is set up on a level, stable surface to prevent external vibrations from affecting measurements. It's calibrated according to the manufacturer's instructions to ensure accuracy.The software connected to the force plate is launched and configured to record GRF at a suitable sampling rate (e.g., 50-1000 Hz, depending on the required detail of analysis).Usually a frequency of 30 Hz is sufficient for most cases. The testing area is cleared of any distractions, and sufficient space is provided for the athlete to stand comfortably.

2) **Subject Preparation:**

The athlete is asked to remove shoes and socks to ensure direct contact with the force plate and minimize any interference from footwear. Of course, test can be performed even when shoes are present, if it is desirable to reproduce more ecological conditions, but having athletes barefoot helps to compare results between different laboratories and studies. Standardized instructions are given regarding the stance to adopt. Considering that the size of the base of support is known to affect balance (i.e., thelargest the distance between feet, the more stable the body is) it is recommended a standardized position with feet axis oriented at 30° and intermalleolar distance of 8-10 cm. The athlete is instructed to stand as still as possible, focusing on a fixed point ahead (3m distance, at eyes level) to minimize head movements.

3) **Measurement Protocol:**

Once the athlete assumes the designated position, a verbal cue indicates the start of the data acquisition. During a period of time of 30-60 s, he/she must avoid any voluntary movement and touch of the hands on the legs. Thirty second is the usual time requested to obtain reliable data when a simple quiet upright bipedal stance is tested. Fore more cchallenging positions (i.e., single-leg stance) 20 s can be acceptable. In this latter case, there are no standardized position, but often the athlete is required to suspend the limb not in contact with the ground at standing leg malleolus height. In other cases, the suspended limb can be placed by pressing firmly the back of the foot against the popilteal fossa of the supporting limb. The execution of at least three trials for each tested condition is recommended, so that the average of the trials can be used as representative of the athlete in a cartain condition/timepoint.

Athlete position on the pressure/force plate. Left: bipedal standing, right: unipedal standing

4) Sensory Conditions:

Measurements are typically performed under different sensory conditions to assess how the body utilizes various inputs for balance control: in the **Eyes Open (EO)** condition, the athlete stands with their eyes open, looking straight ahead. This condition utilizes visual, vestibular, and somatosensory information. In the **Eyes Closed (EC)** condition, the athlete stands with their eyes closed. This condition removes visual input, forcing greater reliance on vestibular and somatosensory systems. Sometimes, a foam pad or other unstable surface is placed on the force plate to challenge the somatosensory system further.

5) Data Acquisition:

During each trial, the force plate continuously records the forces exerted by the athlete's feet on its surface in three dimensions (vertical, anterior-posterior, and medial-lateral). From these forces, the software calculates the instantaneous position of the Center of Pressure (COP).

6) Data Analysis:

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Once the data is collected, specialized software analyzes the CoP trajectory over time. **Key parameters derived from the COP include**: total Excursion/**Path Length** (the total distance the COP travels during the trial, reflecting the amount of sway, expressed in mm), **mean COP Velocity**: the average speed of the COP movement (mm/s), **sway area** (e.g., 95% Confidence Ellipse Area): The area covered by the COP trajectory, indicating the dispersion of sway.

1.5. OK now I know all the theory! Explain me how I can use the DAUVEA sensor kit to test my athletes

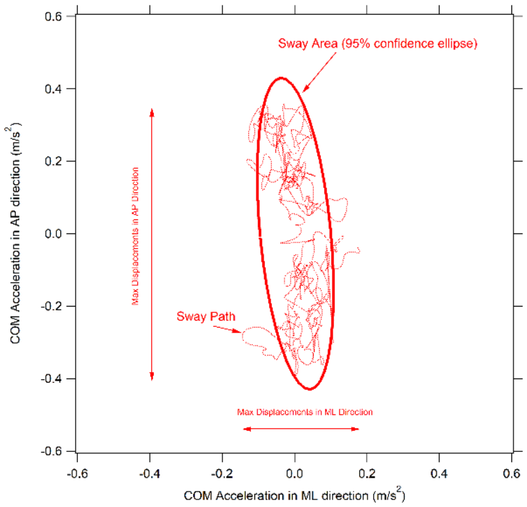
As mentioned before, the use of force plates is typically restricted to the laboratory. But **there is another way to perform a postural sway analysis, using small, lightweight, inexpensive systems like IMU**. Basically, the IMU is a device able to measure accelerations and angular velocities. By placing an IMU close to che center of mass of the body, we can capture the body accelerations. Be aware that a COM acceleration is different by a CoP trajectory, so that the two measures cannot be compared directly. However, previous studies confirmed that COP-derived parameters and IMU/COM-derived parameters are strictly correlated so that is absolutely correct, from a scientific point of view, to assess postural sway using IMUs.

To test your athletes, **the IMU should be placed, using an elastic belt, close to the Center of Mass, that is approximately at L5-S1 vertebrae location. It is very important that the sensor is firmly attached to the body since undesired relative movements between the sensor and the body can alter the results**

Once fixed the sensor, ask your athlete to assume a relaxed standing position with the feet oriented at 30° and intermalleolar distance of approximately 8-10 cm. A paper mask with two properly drawn footprints might help in ensuring a common reference position

During the test, breathing should be normal, voluntary movements avoided and arms should be placed along the body side but not in touch with legs

After 30 seconds, the test is over and we can have a look at the results. The DAUVEA software provide the following parameters (see Figure xx for details)



Sway Area (m^2/s^4): elliptical area containing 95% of the sway path points. Overall indicator of the postural control system performance (i.e. the smaller the value, the better the postural control)

Sway Path (m/s^2): length of the sway path. Informative regarding the correction performed to maintain balance (i.e., shortest path, less corrections)

Maximum COM accelerations in AP and ML direction: define the shape of the ellipse. If one of the two axis is much longer than the other, the subject has a preferential plane of obscillation

The interpretation of the results should take into account several important factors such as:

- **Age of the tested subject**. Postural control develops durinch childhood and adolescence. It remains relatively stable from 16-17 to 25-40 years of age, then slowly tends to worsen
- **Sex of the tested subject**: in young athletes, girls have usually a better postural control than boys. From 16-17 and older, performance becomes similar
- **Fatigue**: postural control should be tested in rest conditions. Of course you can define specific protocols to assess the influence of fatigue on postural control performance
- **Ankle instability or other lower limb injuries**: postural control worsen in case of musculoskeletal disorders or acute injuries. Use this test to assess the recovery from knee/ankle injuries

In the following table are reported some reference values obtained from tests performed at the Laboratory of Biomechanics and Industrial Ergonomics of the University of Cagliari on more than 100 adults aged 18-50. A value should be considered altered when > 2 Standard Deviations with respect to what indicated.

	Bipedal stance	
Condition	**Sway Area**	**Sway Path**
Eyes Open	0.0234	10.3546
Eyes Closed	0.0422	10.9703

	Unipedal stance	
Condition	**Sway Area**	**Sway Path**
Eyes Open	0.2311	23.8669

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Vertical Jump Measurement

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2. VERTICAL JUMP MEASUREMENTS

2.1. Rationale: vertical jump as proxy of lower limb strength

Assessing vertical jump performance in volleyball players is essential due to the sport's inherently explosive and vertical nature. Actions such as spiking, blocking, and jump serving all require athletes to propel themselves off the ground quickly and powerfully to achieve maximum height and precision. The vertical jump serves as a reliable indicator of lower-body power, neuromuscular coordination, and overall athleticism, which are critical for high-level volleyball performance. By regularly measuring vertical jump height, coaches and trainers can gain valuable insights into a player's physical capabilities, identify strengths and weaknesses, and make informed decisions about training programs. For example, an athlete with a below-average vertical may benefit from targeted plyometric or strength-based interventions to enhance power output, while a player showing significant asymmetry between legs may require corrective strategies to reduce injury risk. Additionally, tracking vertical jump over time allows for objective monitoring of performance progress and recovery from injury. It can also serve as a motivational tool, helping athletes see tangible improvements and set performance goals. In elite volleyball, where fractions of a second and inches of height can determine the outcome of a match, optimizing and assessing vertical jump performance is not just beneficial—it's a competitive necessity.encompassing both static and dynamic stability, is crucial for executing complex volleyball actions like jumping, landing, spiking, blocking, setting, and receiving. By assessing balance, coaches can identify deficits and tailor training programs to improve postural control, which directly translates to more efficient movement patterns, greater power generation during jumps, and enhanced agility for quick directional changes on the court. Furthermore, higher effectiveness of the postural control system is associated with a reduced risk of non-contact lower limb injuries, particularly ankle sprains, which are prevalent in volleyball due to the repetitive jumping and landing demands. Therefore, incorporating balance measurements and targeted balance training can lead to improved overall athletic performance and a healthier playing career for volleyball athletes.

Basic information regarding lower limb explosive strength can be obtained by simple aspecific tests like the squat jump (SJ) and countermovement jump (CMJ), wchich are highly useful in evaluating the explosive power and neuromuscular efficiency of volleyball players. Both tests assess vertical jump performance but offer distinct insights into the athlete's physical condition. **The squat jump**, performed from a static, crouched position without any preliminary movement, isolates pure concentric muscle power and is useful for identifying baseline lower-body strength. **In contrast, the countermovement jump**

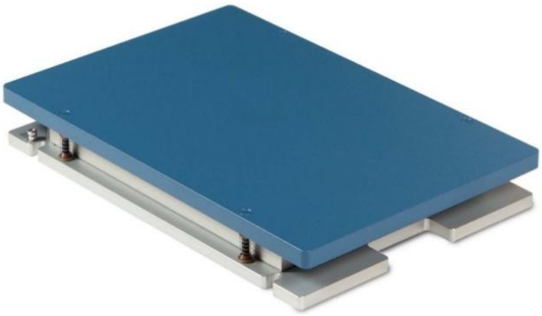
incorporates a rapid downward motion before the jump, engaging the stretch-shortening cycle and providing information about how effectively the athlete utilizes elastic energy and coordination. Comparing SJ and CMJ results allows coaches to assess the athlete's ability to convert stored energy into explosive force, which is critical in volleyball for quick, powerful movements like spiking and blocking. Discrepancies between the two scores may also highlight neuromuscular deficiencies or imbalances, guiding targeted interventions in strength and conditioning programs. Thus, together, the SJ and CMJ tests provide a comprehensive profile of a volleyball player's jump performance and readiness for high-intensity play.several interconnected reasons, impacting both their athletic development and long-term health.

2.2. Instrumental assessment of SJ and CMJ

Instrumental assessment of squat jump (SJ) and countermovement jump (CMJ) provides a comprehensive and highly accurate evaluation of an athlete's explosive strength, power output, and neuromuscular function. This method goes beyond simple field measurements by using **technologies such as force platforms, contact mats, accelerometers, or optical timing systems** to collect detailed kinetic and kinematic data during jumping tasks. These devices allow practitioners to analyze parameters including jump height, ground contact time, flight time, peak force, peak power, rate of force development (RFD), and impulse—all of which contribute to a deeper understanding of an athlete's performance profile.

In the squat jump, the athlete starts from a static position with knees bent (typically at 90-100 degrees) and holds this posture for a few seconds to eliminate any elastic energy contribution. The jump is then executed vertically without a preparatory dip, making the SJ a pure measure of concentric muscular power. **In contrast, the countermovement jump** involves a quick dip or downward motion before jumping, utilizing the stretch-shortening cycle (SSC) to store and release elastic energy. This dynamic movement mimics the natural jumping mechanics used in sports like volleyball, making it particularly relevant for performance analysis.

In laboratory setting, both SJ and CMJ are typically measured using force plates (also known as force platforms) are sophisticated measuring instruments designed to quantify the ground reaction forces (GRFs) exerted by a body standing on or moving across them. Think of them as highly sensitive scales that can measure not just your weight, but also the forces you apply in different directions (vertical, horizontal, and lateral) and how these forces change over time. They typically contain multiple sensors (such as strain gauges or piezoelectric sensors) that detect minute strains when force is applied, converting the effect associated with the application of mechanical forces into measurable electrical signals.



A force platform

A force-time curve obtained during a CMJ using a force platform provides a detailed graphical representation of the vertical ground reaction force (GRF) produced by the athlete throughout different phases of the jump. This curve allows for precise analysis of neuromuscular performance, including timing, magnitude of force production, and power output.

As visible from the following figure, the curve can be subdivided in regions indicating the different phases of the movement:

1) **Standing Baseline:** The athlete stands still on the force plate, producing a force equivalent to his/her body weight (BW). Here the force curve is flat and constant at approximately BW.
2) **Unweighting Phase (UP):** The athlete begins the countermovement by rapidly dipping downward. The force decreases BW as the center of mass descends.
3) **Braking Phase (BP):** As the athlete decelerates the downward movement, force rapidly increases above BW. This phase reflects eccentric muscle action and energy storage via the stretch-shortening cycle.
4) **Propulsion Phase (PP):** the athlete reverses direction and starts pushing off the ground. Force continues to rise and peaks just before take-off. This is where peak force, rate of force development (RFD), and impulse are measured.

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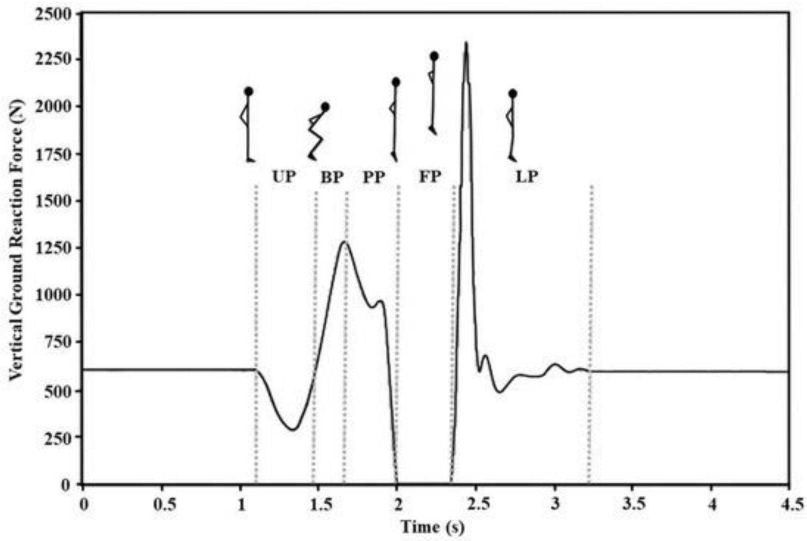
5) **Flight Phase (FP):** once the athlete leaves the ground, force drops to zero (there is no contact with the platform). The **"time of flight"** time (duration of zero force) is used to estimate jump height.
6) **Landing Phase (LP)** (if included): Upon landing, there is a sharp spike in force as the athlete contacts the platform again.



Typical Force-Time curve obtained from a CMJ

By comparing SJ and CMJ performance, practitioners can derive valuable metrics such as the **eccentric utilization ratio (EUR)—the ratio of CMJ to SJ jump** height or power—which indicates how effectively an athlete uses stored elastic energy during movement. **A higher EUR generally reflects better neuromuscular coordination and elastic energy utilization, which are essential qualities for explosive movements in volleyball**, such as spiking, blocking, and serving. Furthermore, force-time curve analysis can reveal asymmetries between limbs, delays in force production, or fatigue-related changes, which are crucial for injury prevention and rehabilitation.

Overall, instrumental assessments of SJ and CMJ offer a scientific, data-driven approach to evaluating and enhancing volleyball performance. They help coaches and sports scientists identify specific physical limitations, monitor training progress, and design individualized interventions that target an athlete's unique needs. This level of precision makes these assessments an indispensable part of modern athletic development and high-performance training environments.

2.3 Use of Inertial Measurement Units to assess SJ and CMJ

Inertial Measurement Units (IMUs) are compact, wearable sensors that combine accelerometers, gyroscopes, and sometimes magnetometers to measure linear acceleration, angular velocity, and orientation. Their application in sports science has grown significantly, particularly for assessing explosive movements like the SJ and the CMJ. As previously mentioned, traditionally, such assessments relied on force plates (or motion capture systems), which are expensive and confined to laboratory environments. IMUs offer a portable, cost-effective alternative that enables data collection in field settings, such as training grounds or gyms. When positioned on strategic body segments—commonly the lower back, thigh, or shank—IMUs can capture detailed kinematic data during jump execution. For both SJ and CMJ, they can provide key performance metrics including jump height.

Moreover, advancements in signal processing and biomechanical modeling have improved the accuracy and reliability of IMU-derived data, making them suitable not only for performance monitoring but also for injury risk screening and rehabilitation tracking. Overall, IMUs represent a powerful tool for objective, accessible, and versatile assessment of jump mechanics across a range of athletic and clinical populations.

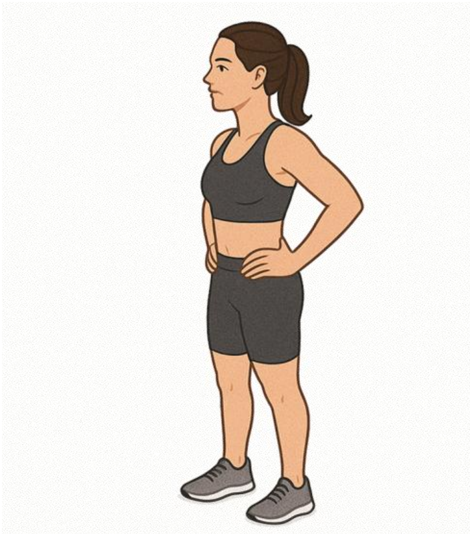
7) **Subject Preparation:**

In the case of the EDATS study, **it is required to the place the IMU approximately at L5-S1 vertebrae position** (i.e., close to his/her Center of Mass). **The device should be firmly fixed against the athlete's body** because any relative motion between device and body can introduce errors in the measuerment. A semi-elastic belt, a suitable pocked located in the shorts or a small rigid clip can ensure that this condition is fulfilled.

8) **Measurement Protocol:**

Ensure the participant performs a standardized warm-up (e.g., light aerobic activity and dynamic stretches). Then, instruct them to stand upright with feet shoulder-width apart and hands on hips (to minimize arm swing influence).**For SJ, the participant should begin from a static semi-squat position** (around 90°-100° knee flexion) and hold it for 2–3 seconds to eliminate the countermovement. The participant should jump vertically with maximal effort, keeping hands on hips, and land in the same spot with knees slightly bent. Ask atheletes to repeat the jump 3–5 times with 30–60 seconds rest between each to reduce fatigue.

In case of a CMJ, instruct the participant to begin from a standing position (similar to what previosuly described), perform a rapid downward movement (eccentric phase) followed immediately by a maximal vertical jump (concentric phase). Be sure that him/her land in the same position, maintaining balance with a soft knee bend. Emphasize the fact that the movements should be continous and smooth (i.e., no pause between the downward and upward phases)



Athlete position on the pressure/force plate. Left: Squat Jump, right: Countermovement Jump

9) Result of the test

Differently from what obtainable in case of a force platform, IMU provide acceleration-time curve that, though, can be processed similarly to what previously described.

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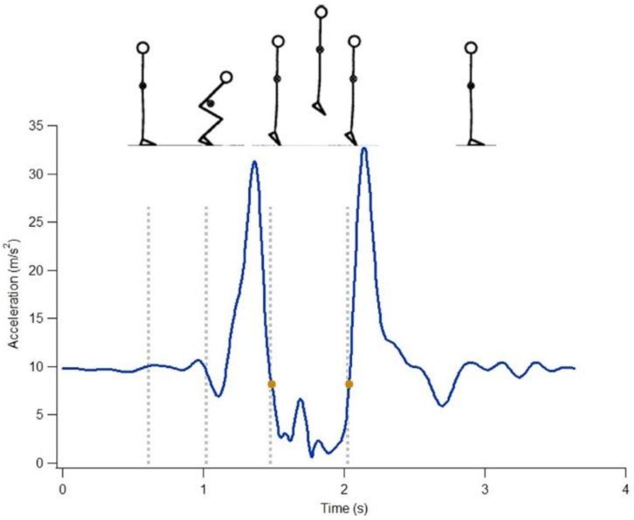

Typical Acceleration-Time curve obtained from a CMJ

2.4 Reference values

Jump height is, of course, affected by many variables including sex and age of the athlete, experience and level of competition, so that is not possible to provide „normal" reference values. However, the following table reports values reported in the literature for volleyball players and other populations (values are expressed as mean (Standard Deviation))

Level/experience	Sex	SJ (cm)	CMJ (cm)
Professional volleyball players (national top level)	M	42.45 (4.68)	46.26 (4.78)
	F	27.15 (4.40)	30.8 (4.70)
Young adults non-athletes (age 20-22)	M	28.33 (6.23)	29.87 (8.89)
	F	18.07 (4.49)	19.1 (4.70)
Adolescents (14-15 years old)	M	18.4 (3.53)	20.78 (3.53)
	F	16.15 (4.95)	16.64 (2.88)
Children (9-10 years old)	M	14.6 (5.19)	16.61 (3.80)
	F	13.47 (4.11)	15.15 (2.78)

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Analysis of Dynamic Balance:
The ”Time-to-Stabilization” (TTS) test

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3. ANALYSIS OF DYNAMIC BALANCE: TIME TO STABILIZATION

3.1 Rationale: why we need to assess dynamic balance in volleyball players?

Volleyball is a high-intensity sport characterized by frequent jumps, rapid changes of direction, and sudden landings, often performed on a single leg. These dynamic actions expose athletes to a high risk of lower-limb injuries, particularly at the ankle and knee joints . In this context, good postural control after landing plays a crucial role in injury prevention and overall performance.

In volleyball, the initial ground contact after a jump often occurs on a single leg.

The *Time to Stabilization* (TTS) is a validated parameter that quantifies how quickly an individual can return to a stable posture following a perturbation, such as a jump landing. It serves as an indirect indicator of neuromuscular control, proprioceptive integration, and effectiveness of sensorimotor strategies.

Measuring TTS in volleyball players is relevant for several reasons:

- **Injury risk monitoring**: Delayed stabilization times have been associated with chronic ankle instability and with increased likelihood of non-contact ACL injuries, especially in female athletes.

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- **Detection of asymmetries**: Side-to-side differences in TTS may reveal functional deficits that are not evident during clinical tests or static balance assessments.
- **Performance profiling**: TTS can help discriminate between different levels of neuromuscular readiness, providing insights into fatigue, rehabilitation status, or adaptation to training

3.2 Instrumental assessment of dynamic balance

Dynamic balance can be assessed in various ways, one of which involves evaluating the ability to restore postural stability following a perturbation, such as a jump landing or a change in direction. In sports like volleyball, where players frequently perform explosive and unpredictable movements, this approach is particularly relevant for identifying motor control deficits, preventing injury, and monitoring functional recovery.

The gold standard for assessing dynamic balance is the use of force platforms, which allow for the quantification of postural stabilization through the analysis of ground reaction forces (GRF) in the vertical, anterior-posterior (AP), and medio-lateral (ML) directions. One of the most common dynamic parameters derived from force platforms is the Time to Stabilization (TTS)—a measure of how quickly an individual can return to a stable posture after a perturbation such as a jump landing.

However, the extensive use of force platforms is limited by several practical constraints:

- High cost and need for dedicated laboratory space;
- Limited portability and ecological validity;

To address these limitations, inertial measurement units (IMUs) have been proposed as a valid, low-cost, and field-deployable alternative. These wearable sensors, typically placed over the L5/S1 spinal segment, can capture three-dimensional linear accelerations and angular velocities. By computing the norm of the acceleration vector over time, it is possible to derive a surrogate measure of TTS (often referred to as accelerometric TTS or aTTS), which represents the time needed for the acceleration signal to stabilize within a defined threshold (e.g., ±5% of the baseline value).

Thanks to their portability, ease of use, and reliability, IMUs represent a powerful tool for monitoring dynamic balance in both laboratory and field settings. They support continuous tracking of fitness levels and athletic performance, inform return-to-play decisions, and facilitate performance assessments in volleyball players and other athletic populations.

3.3 A focus on Time To Stabilization

As mentioned, TTS is a quantitative measure of the time required to regain postural stability following a dynamic perturbation, such as landing from a jump. It reflects the efficiency of the neuromuscular system in absorbing impact and re-establishing balance, and it is widely used in both clinical and sport science contexts.

Definition and theoretical background

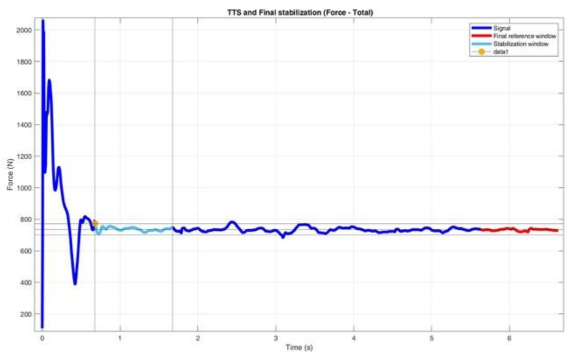
TTS represents the latency from the moment of ground contact (landing) to the moment when body motion parameters—typically ground reaction forces or body accelerations—stabilize within a predefined threshold range. It reflects the dynamic control of posture and provides insight into motor control strategies, including:

- Proprioceptive feedback,
- Reflexive and volitional responses,
- Feedforward motor planning.

Longer TTS values may indicate impaired neuromuscular control and have been associated with fatigue, lower limb injury (e.g., ACL reconstruction, chronic ankle instability), and sub-optimal motor performance.

TTS estimation with force plates

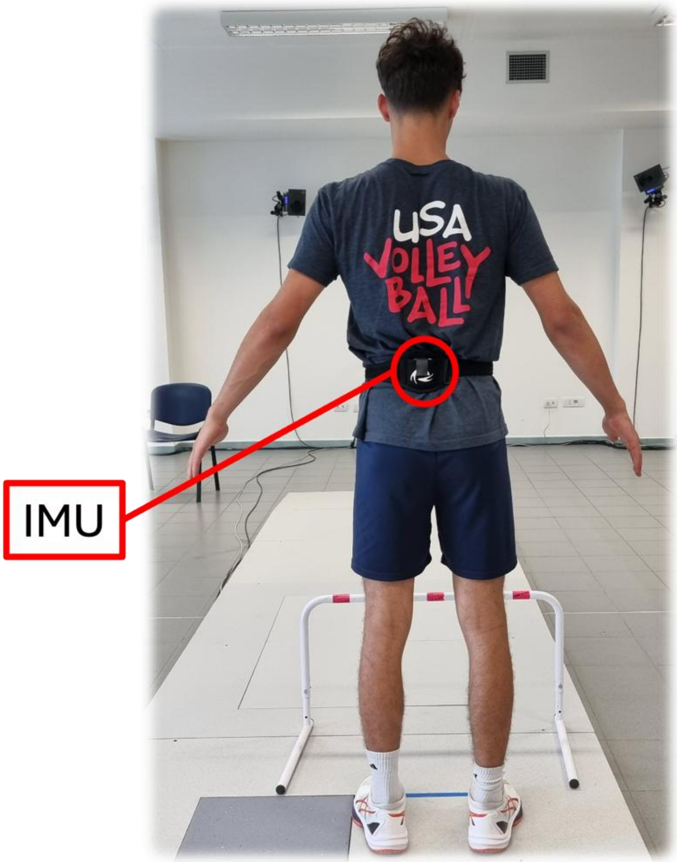
The traditional method uses force platforms to measure the vertical (vGRF) and horizontal (AP, ML) GRFs. The stabilization is defined when the GRF returns to a stable range—commonly within ±5% of body weight for vertical force for at least 1 continuous second.



TTS is the time required to the GRF to stabilize within 5% of the body weight after landing.

Accelerometric TTS (aTTS) estimation with IMU

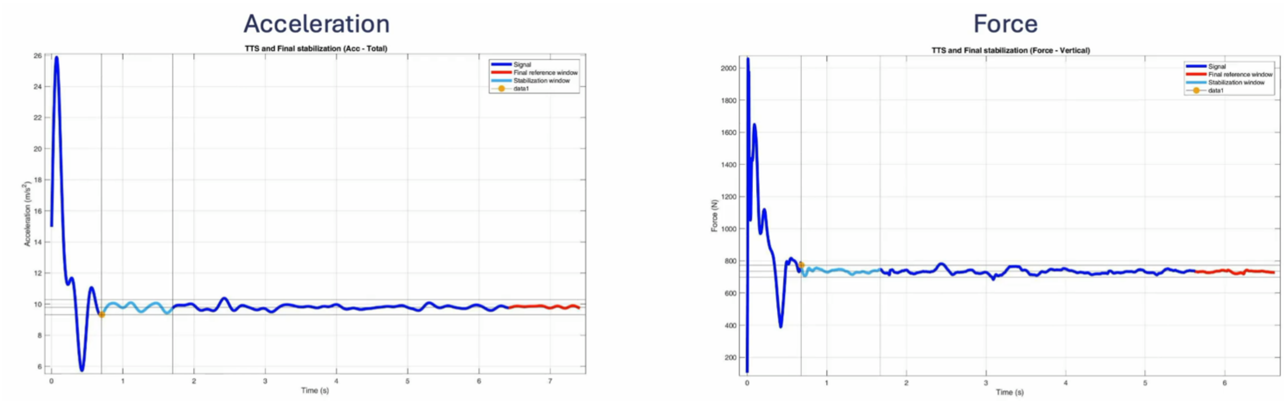
When using an IMU placed at the L5/S1 level, the TTS can be estimated by analyzing the norm of the tri-axial acceleration vector. After landing, this signal shows a transient oscillation that gradually decreases as the subject stabilizes.



The IMU is placed at the lower back (L5/S1) via a semi elastic belt

The aTTS (or IMU TTS) can be defined, similarly to the GRF derived version, as the time from landing to the point where the norm of acceleration remains within ±5% of the baseline (pre-landing) for at least 1 second.

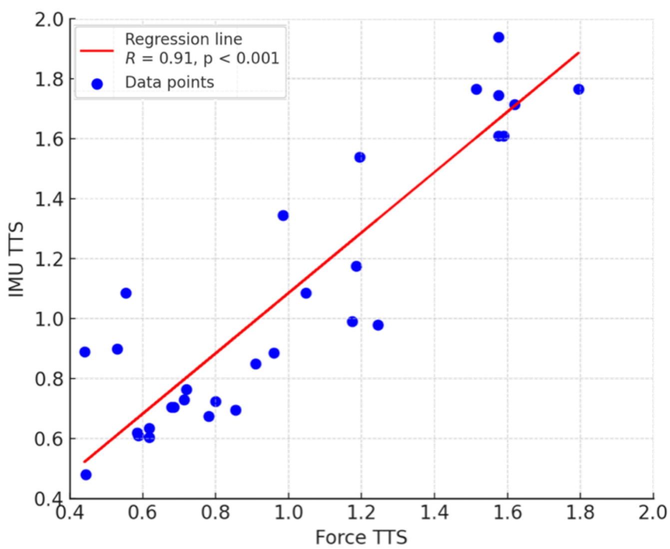
In practice, the raw acceleration signal is pre-processed with low-pass filtering, and landing is identified via a rapid peak in the acceleration norm. From that point, stabilization is computed using a sliding window technique to detect the threshold-crossing segment.



Comparison between the accelerometric and force signals during the TTS task. The yellow marker identifies the TTS.

Comparison and reliability

Preliminary tests show strong agreement between force plate TTS and IMU-derived aTTS. IMUs offer a viable alternative for on-field assessments, remote monitoring, and return-to-play evaluations, while retaining meaningful sensitivity to neuromuscular control deficits.



Correlation between IMU- and Forceplate-derived TTS.

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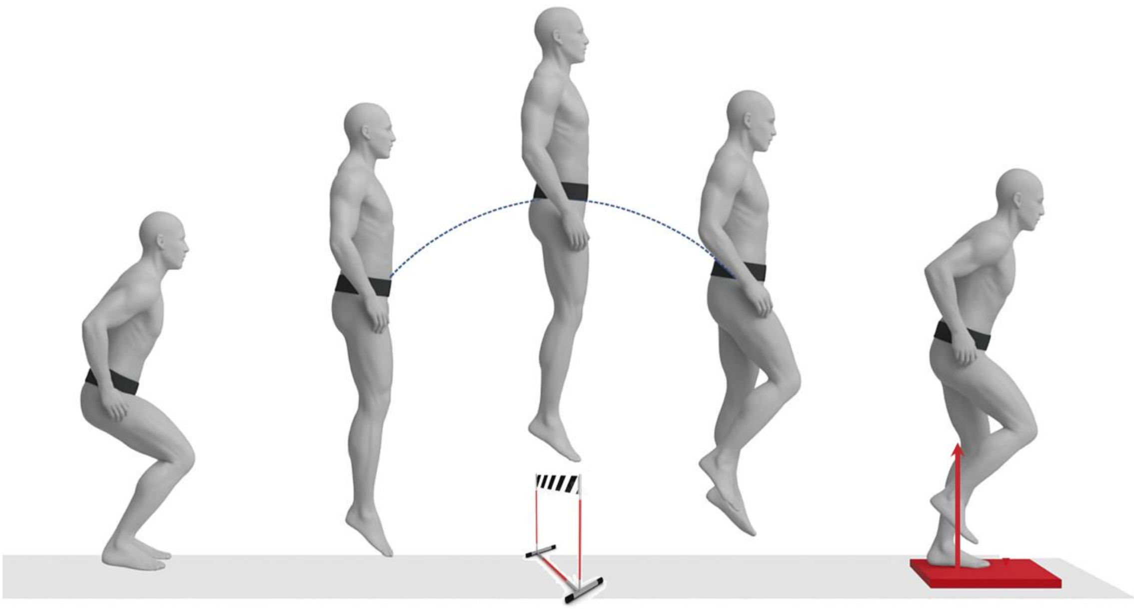
3.4 In practice how do we measure TTS?

While the theory behind TTS is essential, what really matters to coaches and practitioners is how to implement this in practice. So, let's walk through a standard laboratory procedure for assessing TTS and see which parameters we can get from a single-leg landing test!

The test is simple: the athlete performs a forward submaximal jump over a 35 cm hurdle from a starting line placed at a distance equal to 40% of their height from the starting point of the landing platform, and lands on a single leg. Upon landing, they are instructed to stabilize as quickly as possible and maintain the final position for at least 5 seconds until a verbal cue signals the end of the trial. The task mimics a common sporting action—jump and land—and challenges the body's ability to rapidly regain postural control. The test is typically performed under standardized conditions, either barefoot or wearing sports shoes, depending on whether the goal is laboratory reproducibility or ecological validity. Three valid trials per limb are usually recorded.



Schematic illustration of the single-leg landing task used for Time to Stabilization (TTS) assessment. Participants jumped forward from a standardized height and landed on the dominant leg on a force platform. Ground reaction forces were recorded to compute the TTS, defined as the time required to achieve and maintain dynamic postural stability following landing.

Using an IMU to calculate aTTS (in seconds): the main outcome. Shorter times = better postural control we can also obtain information on

- Jump height (optional): estimated from the flight time.
- Stabilization curves: useful to check trial quality and individual landing behavior.
- Symmetry: if you test both legs, you can compare aTTS right vs left and look for functional imbalances.

Why is this useful?

Because longer stabilization times may indicate:

- fatigue,
- neuromuscular inefficiency,
- past injuries (especially ankle or ACL),
- or just a need for more proprioceptive training.

The bottom line? You can use TTS testing to:

- track progress over time,
- support return-to-play decisions,
- identify hidden balance deficits in otherwise fit athletes,
- or simply monitor training effects on postural control.

3.5 OK now I know all the theory! Explain me how I can use the DAUVEA sensor kit to test my athletes

As detailed in previous sections, the TTS is a valuable parameter to assess dynamic balance. While traditional force plates offer a reliable measurement, their cost and limited portability restrict their use to lab environments. Thanks to wearable systems like the DAUVEA sensor kit, we can now bring dynamic balance assessment directly into the field, training rooms, or sports facilities—without compromising accuracy.

The kit includes a lightweight IMU that records body acceleration in three directions and angular velocities. By placing the IMU close to the body's center of mass (roughly over L5–S1), we can obtain an indirect measure of how long it takes to regain a stable posture after a dynamic perturbation, such as a jump landing.

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To perform the test:

- Position the sensor on the athlete's lower back using the elastic belt provided.
- Make sure the sensor is tightly secured to minimize artefacts due to skin/sensor slippage.
- Instruct the athlete to perform a submaximal forward jump starting with a two-legged take-off and landing on one leg (single-leg landing).
- Ask them to stabilize as quickly as possible after landing and maintain their position for 5 seconds.

The DAUVEA software will process the acceleration signal automatically and return the following parameters:

- aTTS (accelerometric Time to Stabilization): the time it takes for the signal to return within ±5% of the baseline for at least 1 second, starting from the moment of landing. This is the main indicator of dynamic balance performance.
- Jump height (optional): estimated from flight time using vertical acceleration data.
- Symmetry: by testing both legs, right vs left aTTS can be compared for functional imbalances.

Important tips for valid and reproducible testing:

- Ensure the athlete is not fatigued, as neuromuscular performance may be altered.
- Repeat the test three times per leg, and use the average value for interpretation.
- Make sure the athlete understands the importance of a controlled landing and quick stabilization.
- Record any unusual behaviors or loss of balance for each trial.

Like in postural sway testing, TTS should be interpreted based on individual factors such as:

- Age and sex (young athletes may stabilize faster; males and females may differ depending on sport and training age),
- Fatigue level (compare pre/post training or match),
- Previous injuries (e.g., ACL, ankle sprains),
- Dominant vs non-dominant leg.

Reference values are currently being developed within specific athletic populations. However, based on preliminary laboratory studies, healthy young adults typically stabilize in less than 1.2 seconds, with elite athletes showing even shorter times (e.g., 0.9 s). Longer times (>2.0 s) may indicate a motor control deficit or need for targeted neuromuscular training.

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