Module 1. Fundamentals of force platform kinetics and their context in sports and clinical settings

Introduction

What are force plates?

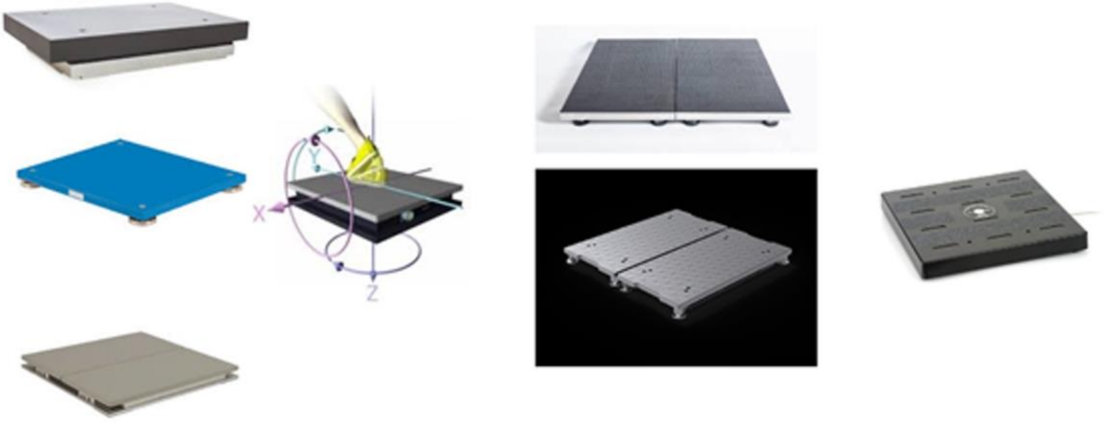
This simple but wonderful technology is, in essence, a very precise and robust weighing scale, combined with a digital clock that measures at a frequency of at least 500 times a second (hertz [Hz] and, more typically, 1000 Hz. Of course, while both a scale and a force platform measure weight or force x gravity applied to them, the sensors within force plates are far more precise than those of your bathroom scale. Sensors in force plates need to be able to cope with individuals running, jumping, and landing across them without being damaged, and maintaining their accuracy and reliability, year after year.

Even though a typical landing from a jump results in impact forces of between 4 to 10 times body weight, in the range of 300 to 1000 kilograms, measurement accuracy may be within a gram. The demands placed on force platforms require not only high-quality load cells (1 in each corner of the force platform), but also a casing that is strong enough to cope with this level of impact and a platform surface stiff enough to ensure that the vibrations or “noise” do not affect the recording of the forces generated by the individual on the platform and their muscle actions. Because of this, metallic bases are generally used which encase the load cells or “force transducers” and the accompanying electronics (amplifier and analogue to digital converter). Therefore, each platform typically weighs at least 8 kilograms, with larger versions as much as 20-25 kilograms.

How do they work?

Load cells are deformed by load (force) applied to them, producing a voltage change proportional to the magnitude of load, which the cell measures. This voltage change is amplified and then converted to a force output. The relationship between voltage changes and force is the basis of the calibration process (a process performed by the manufacturer), whereby the voltage change within each cell across a range of loads is determined.

Figure 1: Examples of vertical and triaxial force platforms and the 3 axes of force.



Triaxial force platforms

Vertical axis force platform

Source: authors own elaboration.

Various types of load cells are used in force platforms –strain gauges, beam load cells, and piezoelectric transducers. Most force platforms available use strain gauges (Figure 1). All force platforms comprise force transducers which measure vertical ground reaction force (vGRF). However, triaxial force platforms also contain sensors oriented to measure force in the medial-lateral (*x*) and anterior-posterior (*y*) axes (see Figure 1). As the force transducer is one of the most expensive components of the force platform, the major determinants of the cost of force platform systems are: the use of vGRF only versus triaxial sensors, higher overload characteristics and accuracy of the force transducers used, and the size of the platforms themselves. Triaxial platforms are substantially more expensive than the vertical axis force platforms now common in sports settings. The availability of a number of lower cost (relative to triaxial systems), smaller, vGRF force platforms in recent years has reduced one of the principal barriers to use in sports and clinical settings.

Historically, (triaxial) force platforms were found in university biomechanics and exercise physiology laboratories, often embedded into a concrete floor, for studies of gait (walking) and other movements. The interest in triaxial platforms, and the justification for the additional expense of this type of hardware and associated costs of installing into the floor, is obvious in the analysis of horizontal activities where the individual walks, runs, sprints across, or changes direction on the platform. While there is a wide variety of movements and components of sports performance that can be evaluated with force platforms, it is notable that it is the single axis vGRF platforms and vertical assessments that have been at the core of athlete neuromuscular performance assessment and monitoring within the sports institutes with a substantial history of force platform use (such as the English, Australian, and

Canadian Institutes of Sport and the US Olympic Committee). Single or pairs of single axes vGRF force platforms are now found not only in the large sports medicine institutes such as Aspetar and the Sports Surgery Clinic, but also in smaller clinics and even gym settings.

Unit 1.1 vGRF platforms use in sports and clinical settings

In both Olympics and professional sports, the most commonly implemented tests with vGRF platforms are variations of the vertical jump, such as the countermovement jump (CMJ), squat jump (SJ), drop jump (DJ), single leg countermovement jump (SL-CMJ), and isometric tests such as the mid-thigh pull, squat, or variations of posterior chain assessment. Most of the literature around force platform applications in healthy and rehabilitating athletes has been dedicated to the evaluation of the lower extremity; however, the evidence for and the use of dynamic and isometric upper extremity in athlete profiling and monitoring have been accumulating in recent years. These isometric and dynamic assessments are strength/power performance/diagnostics which are commonly implemented as part of preseason or other periodic profiling battery. In environments where force platforms are not available, the same tests or variations thereof are generally performed using other equipment/devices (i.e., contact mats/optical devices), although, as discussed later they measure jump height, but not the assessment of kinetics during jump-land activities that force platforms allow. Kinetics is defined as the study of forces and/or torques (rotational forces) during a movement or activity. Force platforms measure force applied over time, and, during isometric tests (with no movement), we report force-time variables such as force, rate of force, and impulse (force * time), while during jump-land activities and other movements additional information is derived.

Movements can be described both by their kinematic and kinetic characteristics. Kinematics describes the trajectories of the body and individual joints and properties such as velocity and acceleration, contributing to a visual analysis of discrete movement (such as jump test) or a skill (such as throwing). In dynamic assessments on force platforms, in addition to force-time characteristics, velocity, power, and displacement of the athlete’s centre of mass (not of individual joints) are derived, and a comprehensive kinetic analysis obtained, differentiating it from the single performance output (jump height) obtained with other devices.

Jump testing versus force platform jump testing

Optical devices and contact mats can measure flight time during jump tests, from which jump height is estimated (via the flight time method). It is the most commonly reported output in jump tests whether they are performed on force platforms or not. On face value, and to the athlete, the only difference between performing a countermovement jump on a contact mat and on a force platform is the surface they are stepping onto. To the practitioner, the differences are huge. When a CMJ, SJ, or SLJ is performed on a contact mat, it measures one thing: flight time, and from this value estimates jump height (and, in some cases, peak power, using prediction equations that include jump height and body weight (Sayers et al., 1999) or body composition (Gomez-Bruton et al., 2019; Güçlüöver & Gülü, 2020). In contrast, a dual force platform system may provide > 100 kinetic variables (bilateral, individual limb, and asymmetries), in addition to jump height and peak power (themselves potentially determined more accurately). However, it is important that not only the practitioner, but also their colleagues understand that the added value of performing a jump assessment on a force platform is not that it may improve the accuracy of jump height measurement. The added value relates to it providing, in a simple test that athletes are familiar with, both jump height - a recognisable performance output with well-established associations to sprint, acceleration, and deceleration ability (Harper et al. 2021, Loturco et al. 2015), with value in for some sports/positions as a performance indicator and skill, and some capacity to assess acute, residual, and chronic response to competition, training, and load; and a wealth of vertical ground reaction force (vGRF) derived kinetic data, relating to the magnitude, timing, rate of, force and of phase-specific impulse, velocity, power, and displacement.

Over the last 15-20 years, evidence has accumulated that the kinetic data obtained during the jump and landing phases can provide additional insights into athlete neuromuscular qualities beyond that of jump height alone. Similarly, in a regular monitoring context, jump height may suggest recovery of an athlete from a fatiguing competition or training bout; while kinetics reveals deficits (Cormack et al., 2008; Gathercole et al.,2015). Conversely, positive responses to load or rehabilitation may not be evident or expressed by jump height, but are evident in kinetic variables (Lonergan et al. 2022). It is this potential for identifying aspects of athlete status and changes in that status that *may* not be revealed by jump height that provides the added value to the performance and medical team and is the fundamental justification to stakeholders when seeking the purchase and integration of force platform technology.

Performing a jump on force platforms transforms the test from a measure of jump height and its correlates to an assessment of lower body kinetics with the potential to provide substantial additional insight into lower limb neuromuscular performance qualities.

Overview of applications of force platform testing in sport

Fundamentally, the kinetic variables derived from dynamic and isometric force platform assessments all aim to characterise and quantify some aspect of athlete neuromuscular performance or “neuromuscular qualities”. Some of these qualities overlap and are highly correlated with each other, and others show greater independence, indicating they represent different aspects of neuromuscular or musculotendinous function. The qualities represented by jump variables may relate to athletic performance, and / or to susceptibility to injury or resilience or “robustness” (i.e., ability to cope with the demands of competition and training load); therefore, they contribute to the characterisation of the athletes’ neuromuscular performance, and potentially, risk profile. Some of these variables are quite stable while others are also very responsive to loading and are, therefore, useful indicators in more frequent monitoring aimed at characterising acute/residual fatigue. Thus, we can broadly categorise the applications of these assessments into three types:

Profiling: this denotes tests applied periodically, such as the start and end of preseason or the preparation phase in Olympic sports, examining an athlete's status at a given time point and is typically partly aimed at characterising the athlete in relation to the other athletes in their team or sport and identifying neuromuscular KPIs. Repeating this after a period of weeks or months, following a defined cycle of training or period of competition, aims to examine chronic adaptations or detraining. Profiling includes consideration of both performance-related and injury-risk-related qualities. To maximise the ability of these assessments to quantify chronic adaptations, they should be conducted under conditions which minimise the influence of acute or residual fatigue on performance i.e., not assessing 24-48 hours post-match or intense training.

Load-response monitoring: this application denotes a frequency of assessment, such as weekly, biweekly, or more frequently. In team sports with long seasons and dense competitive schedules, or in tournament situations in individual or team sports, this is generally implemented in order to characterise the evolution of neuromuscular status and identify abnormal changes which might indicate negative adaptations or incomplete recovery. This load-neuromuscular response data is typically considered alongside other indicators of load response in informing decisions around short-term alterations in training load or recovery strategies in individual athletes). Incomplete recovery from competition and training load may eventually accumulate to impact negatively on competitive performance. Therefore, these types of assessments are more focused on tracking individual changes and are typically conducted 2 days after a match and/or 1-2 days prior to another competition ("readiness") with the specific timing depending on whether data is used to influence training load modifications/recovery strategies and/or athlete deployment within the competition.

This frequent monitoring approach is most associated in the literature with the detection of negative adaptations i.e., fatigue, but it should also be understood as a tool to identify underlying positive adaptations in neuromuscular performance, which may not yet manifest in improvements in other external performance measures including jump height. These may result from competition exposure and adequate recovery or from a conditioning intervention during a preseason targeted to specific aspects of neuromuscular performance. Early confirmation of the efficacy with which the stimulus is producing these desired effects is valuable.

Rehabilitation/RTS: this application has three components, discussed in more detail in another course of this certificate:

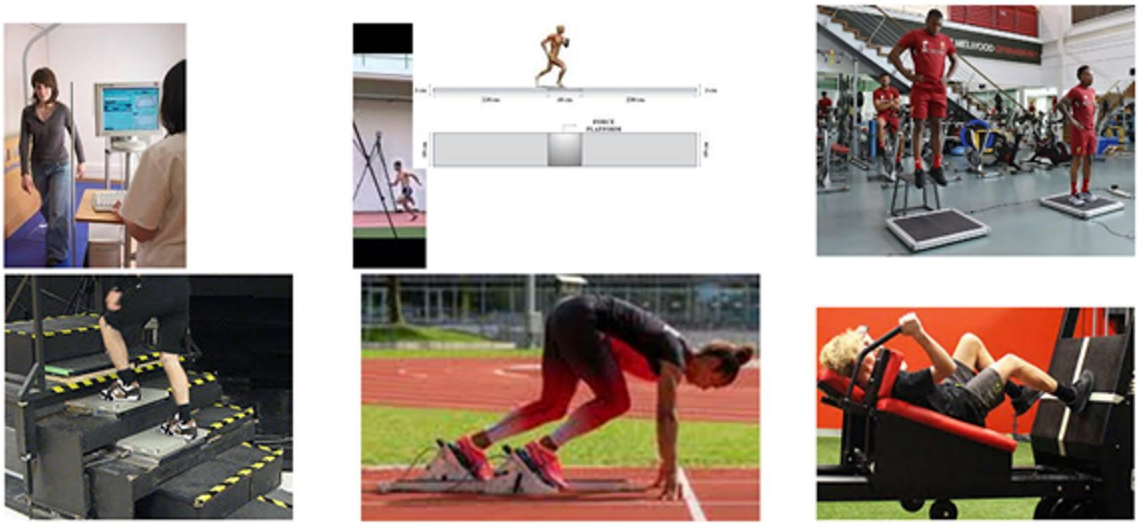
- Using profiling data taken when the athlete was healthy, as benchmark data used to inform decisions on return to sport or phase progression during rehabilitation.

- Quantifying chronic trends in rehabilitation—i.e., overall bilateral neuromuscular performance and in the injured and uninjured limb.
- more frequent load-response monitoring (as described above for the healthy athlete) to establish an acute and residual response to loading as an indicator of the ability of the injured limb to cope with specific training sessions or increments in loading.

Therefore, the profiling and load-response approaches described above in the healthy competing athlete are also applied to the rehabilitating athlete, but, additionally, there is an increased interest in trends in individual limbs (particularly the injured limb) and asymmetries, as well as injury-specific and player specific contextual factors that influence the design of testing protocols and interpretation of data, hence warranting separate treatment within course "Injury and Rehabilitation Kinetics and Kinematics".

It is important for practitioners to be aware that, while often the comprehensive kinetic analysis *may* reveal additional information that informs the above applications that jump height or other classically reported variables, this does not mean they will always do: some athletes express a similar magnitude and direction of (positive or negative) response in jump height as is revealed by kinetic variables. Jump height should always be included in profiling and monitoring trends and not be completely ignored in favour of kinetic variables.

Figure 2: Some dynamic activities measured with standard/bespoke force platform systems.



Clinical studies of gait and daily activities

Sprint starts and maximum velocity

Jumps and ballistic exercises

Source: authors own elaboration

In addition to floor mounted or embedded platforms, some sports institutes have invested in custom-made plates embedded into start blocks for sprinting, mounted on leg press machines (figure 2) or in rowing machine footplates, to measure force production in sports-specific positions.

The use of vGRF force platform technology versus triaxial platforms and biomechanics in sports medicine/clinical settings

While vGRF platforms are now commonplace in sports settings, triaxial force platforms combined with motion capture technology allowing 3-dimensional kinematics with some exceptions in professional and Olympic sports, are still predominantly found in larger sports medicine/research centres such as Aspetar (Doha, Qatar) and the Sports Surgery Clinic (Dublin, Ireland), as well as university laboratories. The combination of kinematic data from high-speed cameras which track markers placed on clothing or the body of the individual (or from other devices which provide kinematic information) and kinetic data from the force plates enables full biomechanical analysis of a movement in performance and injury rehabilitation is covered in more detail in other parts of this certification.

The kinetic data from the force plate provides the indirect measurement or external force produced by muscle contraction acting on tendons. As such, in any activity which involves force production emanating from more than one joint, the kinetics analysis provides force data which represents a summed output across these joints, and the velocity and displacement obtained represent the velocity and displacement of the centre of mass. Displacement of centre of mass in a countermovement correlate highly with knee flexion, but it does not actually measure it. Therefore, the kinetic data does not allow us to quantify the relative contribution of each joint to that output and movement at those joints. Performing the same movement with kinematic information and triaxial force platforms allows the creation and tracking of a 3D image of the skeleton, and through a process called “inverse dynamics”, the force platform kinetic data not only enables the calculation of overall forces and power applied into the platforms, but it also enables the estimation of force and power at each joint. For example, a full biomechanical analysis of a vertical jump would include left and right ankle, knee and hip joint power during the whole movement, as well as joint angles (i.e., flexion, abduction, etc.) and their angular velocities. In theory, a stable total output over time could mask improvements at one joint and decline at another joint, while improvements in total output, for example, following a knee joint injury might be due to improved hip joint compensation rather than progress at the knee.

Full biomechanical assessments are implemented systematically in post ACL athletes periodically (i.e., 6, 9, and 12 months after surgery). Such an assessment, which includes various jumps and hops/change of direction tests, would last around 45 minutes, 15-20 minutes of which would be taken by setting up markers. In addition, the gold standard in human performance evaluation would combine this biomechanical analysis with electromyography (EMG) in order to estimate the relative activation and contribution of specific muscles during the activity, in addition to joint power outputs provided by the kinetic-kinematic data. In the hands of experts, this information can provide additional insights into the status and progress of an athlete through rehabilitation or the effect of a training program.

Practical considerations

While the combination of 3D motion capture and triaxial force platform technology is very costly (150,00 Euros), it is other practical limitations (in particular, the time costs and the complexity associated with 1) setting up an athlete for these tests, 2) data processing, and 3) data interpretation, i.e., generating meaningful, actionable information about the athlete, which prevent this type of set-up from becoming systematically applied in team sports settings. While time costs associated with setting up an individual to be tested using marker-based systems (discussed in module 3 of this course) are reduced with non-marker inertial measurement unit (IMU) based systems, there remains a large processing time/expertise cost, based on the substantial increment in information provided by 3D kinematics. This increment increases not only processing time, but also time required for interpretation and feedback, which will need to be provided by a biomechanistic or a sports professional with specialised experience in this process. Although bio mechanists are employed within national sports institutes, they are rarely present within team sports settings. Therefore, in the professional leagues, team sports in particular–La Liga, Premier football, NFL, the NBA, and MLB –the substantial costs of a biomechanics lab are not the main limitation to use. Hence, very few teams within these leagues routinely implement biomechanical analysis, and those that do implement it only do so periodically, (such as at the start of a season), often with this service provided by an external consultant.

Practitioners who do work in environments without the equipment and/or the technical knowledge should be aware that while kinetics provides a huge amount of insight into athlete status and responses, there may be cases in which tremendous information value is gained by bringing such a specialist in to evaluate a player or players, or taking them to a centre that can provide this service. For example, it may be warranted to evaluate a single player at specific intervals during their rehab or to gather further detail in a healthy athlete on a key aspect of movement critical to performance, particularly if this movement is complex, involving coordination of multiple joints such as throwing in baseball or cutting or changing direction in multidirectional sports.

In other courses within this certificate the use of kinematics alone or in combination with kinetics in the healthy and injured athlete. In contrast, even without a biomechanics background, the information from this certificate will provide you with enough knowledge to collect and interpret vGRF kinetic data and variables derived in such a way as to profile and monitor athlete status and inform practice.

Nonetheless, in a similar way as described above, that when moving from optical/contact mat technologies with jump height as the output to obtaining vGRF kinetics from the same activity, the additional information gained from performing the same activity with kinematics will provide additional data. This data provides additional insights that *may or may not* alter the interpretation of the information generated in the kinetic analysis, and further inform practice. However, a thorough grasp of the wealth of information provided by dual platform vGRF kinetic analysis and of its use is a prerequisite to develop the ability to identify what additional information can be gained from kinematics and to understand when that information is critical to problem solving, i.e., when to insist on that step for a given athlete or wider team level performance or injury related question. Therefore, regular vGRF testing may be complemented by periodic analysis with 3D kinematics in athletes identified as having a profile of concern based on vGRF kinetics.

The advantage associated with the on-site accessibility (i.e., low time cost, rapid data processing and generation of meaningful reports) of single axis vGRF data from jump and isometric assessments is the feasibility of frequent implementation, even in team sports/squad settings.

Furthermore, the increasing sophistication of vGRF data analysis in the countermovement jump can provide proxy estimates of joint/muscle contributions or inter-joint coordination strategies to practitioners who only have access to force platforms. These estimates are based on research which has combined vGRF and motion capture data; by correlating vGRF profiles (magnitude and timing data) with kinematic and EMG data (to calculate joint-specific angular power and to determine muscle-specific contribution, respectively) during phases and subphases.

This on-site, instantaneous access to detailed neuromuscular assessments via comprehensive vGRF force platform kinetic analysis has revolutionised the power of the practitioner to ask questions about athletes' neuromuscular status and about their responses to training competition or to rehabilitation. This has also converted force platform use as a strength and power diagnostic tool from one which was previously confined to preseason/post-preseason (1-2 year) “profiling” to one that is used in “load-neuromuscular response monitoring” within and across micro-cycles. As such, 2-3 days post-match assessment is common in professional football, Rugby and the NFL, with others testing twice weekly.

Unit 1.2 Contemporary force platform use in sports performance and sports medicine

The widespread use of force platform technology in professional sports such as football, basketball, rugby, and baseball are relatively recent (2016 and beyond). For example, at the start of the 2015/2016 season, two of the 20 English Premier League teams were using force platforms; at the start of the 2019 season, more than 15 were. In the NBA, approximately 4 teams were using force platforms in 2015/2016, and in 2019 more than 24 of 32 were. This exponential increase cannot be principally attributed to changes in hardware, as this has not evolved dramatically. The emergence of relatively economical, single axis portable force platforms with instantaneous data processing of vertical GRF data, providing both meaningful real-time results and a comprehensive analysis of force, power, impulse, and velocity displacement that can be interpreted by a variety of sports professionals without a higher level of biomechanical training has transformed force platform technology into one of the most common tools of athlete assessment and a consistent feature of training grounds in professional leagues worldwide. Therefore, the critical element in this transition from lab to training ground has been the delivery of software that does the following:

- It enhances the workflow during test performance, minimising athlete wait time and maximising the number of athletes that can be tested in a time period (as team sport testing generally operates under tight time constraints).
- It provides immediate data feedback. To enhance athlete engagement, immediate feedback on some simple metrics is critical, potentially it is motivational and improves compliance.
- It automates data analysis (conversion of raw signals to metrics or variables of interest).

Today, in most sports and clinical settings, a sports scientist, a strength and conditioning coach, a physiotherapist or sports therapist, or a sports medicine doctor implements force platform assessments at the team’s training centre. They will often be expected to deliver that information to colleagues and coaches within minutes or hours after the completion of tests. The athlete will also expect some immediate feedback from the test, providing some simple and recognisable data such as jump height, in context, that is referenced to their previous performance(s) or to the team as a whole, enhances most athletes' interest in doing the test and the likelihood that they will put in the maximal effort into performing it.

Conversely, settings which provide no feedback of this nature often fail to build buy-in amongst the athletes so that fewer participate, making it harder to understand overall team trends, while those that do participate may not be as motivated as they could be, reducing the value of the data (as these tests usually aim to quantify the athlete’s maximal capacity at a given time-point).

Therefore, it is probable that the force platform systems a practitioner will encounter in today's sports and clinical environments are contemporary systems with software that include automated "event" detection and analysis.

What are events?

In the context of jump and isometric assessments, "events" refers to a specific point within the movement or contraction such as the start of movement, start and end of phases, the take-off and the landing in the jump, or the onset of contraction in an isometric test. Event identification by an objective criterion is necessary during the processing and conversion of the raw force-time signal to meaningful variables linked to movement and or neuromuscular qualities.

However, if you are accessing a system in a local university, you may not have access to proprietary software which automatically processes and analyses raw data. If adequate relevant kinetic variables are not being generated, you will need to export raw data and process it using a tool such as Matlab or Excel. This is far from ideal in the fast-moving environment of high-performance sports, and the instantaneous processing that proprietary systems provide is highly preferable. However, if budget constraints prevent this, there are some excellent resources which provide a step-by-step guide and resources for doing this in Matlab or Excel if auto analyses software is not available (Chavda et al. 2020).

Advantages and disadvantages of automated processing

A huge amount of time is saved by software systems which auto-calculate metrics. Previously, the raw force-time data would need to be entered into a spreadsheet set up to convert this data to variables of interest. However, a negative consequence of this new system has been the loss of the need to understand how the processing takes place and with it the ability to problem solve if outputs are erroneous. It is important to know that all variables derived from the force-time curve depend on algorithms and predetermined thresholds for detection of key events –such as the start of movement, take-off and landing in the case of jump–, as well as that the assumptions on which these are based can be violated, potentially without the practitioner being aware, other than recognising values that are generated as being erroneous. Therefore, even if one has access to auto-calculate systems, in order to identify and solve erroneous data, it is critical for the practitioner to have:

1. A working knowledge of how numbers are arrived at –the steps in going from a raw force-time to the generation of metrics.
2. Some concept of expected values for key variables –which helps to identify failure of the algorithms in phase detection and / or calculations.

3. An ability to qualitatively (visually) assess force-time, velocity-time, power-time, and displacement-time curves and to identify anomalies which are common causes of erroneous data.

It is also important to recognise that there is no “perfect” approach to event detection, and some approaches that work well in a lab situation or in a “clean” environment may be less appropriate in noisier, less controlled situations. Similarly, detection thresholds that work well within the “normal” range of body weights, may pose issues with very heavy or light athletes. Some auto-calculation systems allow you to choose from several options for these detection thresholds whereas if you are using other means such as Excel or Matlab to process data, you will have to decide which to use (the methods most commonly used for the CMJ are discussed in module 2 of this course). Similarly, it may surprise learners who are new to the use of force platforms that the most fundamental and commonly reported of all metrics in jumping ―jump height― is typically calculated (estimated) in two different ways: the flight time method and the impulse-momentum method or “theorem”, both of which have flaws and can lead to quite different results. Before discussing this, it is useful to understand the process by which various outputs are derived from the force platform, what the force platform actually measures, i.e., the raw data force-time record.

While the steps by which variables are calculated may seem abstract and academic to the practitioner who simply wants to determine the status of your athletes and potential positive and negative adaptations, this information is important for the following reasons:

1. As highlighted above, it gives you an insight into the assumptions upon which variables are calculated and events are detected, and will therefore help you understand and possibly resolve/fix trials that a proprietary software has miscalculated, misidentified or not identified at all.
2. It develops your ability to query “black box” indexes or variables, and critically evaluate and understand new variables in the literature or added to software.

Force-time data is measured; all other data is derived

The process by which force plate measured vGRF is converted to the variables used in profiling or monitoring athletes is based on Newton’s three laws of motion (see below). Whether this is automated in the force plate system software or you are doing these calculations in a bespoke or existing spreadsheet or script, having a basic grasp of these laws in the context of human movement is essential knowledge. This is the basis for understanding how, from the raw force-time curve obtained by the force platforms, the other profiles (velocity-time, power-time, displacement-time) and, ultimately, the variables that you will use are derived It is important to be clear that only force-time data is *measured* while the remainder of the physical characteristics are *derived* from this raw data, and not measured directly. This is somewhat analogous to skinfold estimation of total body fat, where calipers measure subcutaneous fat (equivalent to the force platforms measuring force-time during a movement), but fat in other sites and total body fat are estimated according to established associations between subcutaneous fat and fat in other sites.

Instead of estimating total body fat from subcutaneous fat, an association which varies according to age, gender, and ethnicity, deriving velocity, power and displacement time profiles from force, is based on laws of physics which do not vary according to who the athlete is. However, because these calculations are based on some simple assumptions, the validity and accuracy of outputs depend on the degree to which the practitioner can ensure that these are being met. Ensuring these factors are attended to aims to ensure the values are valid, i.e., how closely they represent the true value for that variable, and, therefore, is directly linked to the accuracy of the assessment. Paying attention to this will also improve reliability (the degree to which the values are repeatable under the same conditions and athlete status), but maximising reliability also depends on other factors discussed below and in module 2. Here we outline only the factors that influence validity and accuracy of the measurement of variables.

Note that if you have been implementing jump tests using a contact mat, optical device, or mobile app, these factors would not have been of concern. In this sense, there is an additional “cost” associated with the “benefit” gained from the huge increment in detailed information gained about athlete status derived from measuring the same activity using highly sensitive force platform technology. The “cost” of this data wealth is the need to pay much greater attention to implementing protocols than when doing the same test on a device which only measures jump height/contact time. For example, when performing a jump test on these devices, it would not have been necessary for the athlete to be still for 1-2 seconds prior to the jump to get an accurate weight, and it did not matter if they were rocking from side to side prior to jumping. These elements were not important because weight is not measured with these devices. With force platforms under their feet, these become critical aspects of the jump measurement protocol.

While there is great interest in determining the reliability of hardware, software, and variables, it is critical to understand that the manner in which the practitioner runs a test protocol has a large and overriding influence on the validity, accuracy, and reliability of the data. For this reason, italics are used above when stating that performing a jump on a force platform gives “*a potentially* more accurate measure of jump height”. The protocol used, the instructions you give, the athlete’s understanding and adherence to those instructions, and your ability to detect and correct failures to adhere to such instructions in real time may be the most important determinant of these three aspects of measurement. The consistency or reliability which you engineer within your environment directly affects your ability to detect meaningful biological response/adaptation (“signal”) and to distinguish that from random variations in the way the test has been set (“noise”).

Key general considerations in force platform testing and approaches to these assessments that maximise the potential of collecting valid and “clean” data are detailed in several sections of this module, and specifics related to each test in their respective modules. Before developing a wider knowledge of force platform use, it is useful to first understand how information is derived from the CMJ as we start developing an understanding of the process of generating information from force-time data on athlete status.

Force fundamentals

First, consider Newton’s laws of motion upon which these calculations are based.

- First law of motion

If no force is acting on an object, it will either remain at rest or at a constant velocity; i.e., without force, there will be no change in movement.

- Second law

The magnitude of an object's acceleration (rate of change in velocity) is directly related to the forces applied to it in a proportional way. This can be seen in the equation *force = mass x acceleration*. When rearranged, with this equation we can calculate acceleration with a force measurement (applied to the platform) and mass (the athlete’s bodyweight). At the start of a jump, if the athlete is standing still, the measured force is equal to the athlete’s mass. However, when they start to apply force or they reduce their effective mass as they lower their centre of mass when descending into the countermovement, vGRF will change and be above or below bodyweight (as on a bathroom scales movement changes your weight –your weight doesn’t change, but your centre of mass does and, therefore, your effective mass (bodyweight x gravity)). When the force applied into platforms decreases below body weight, we also see negative acceleration.

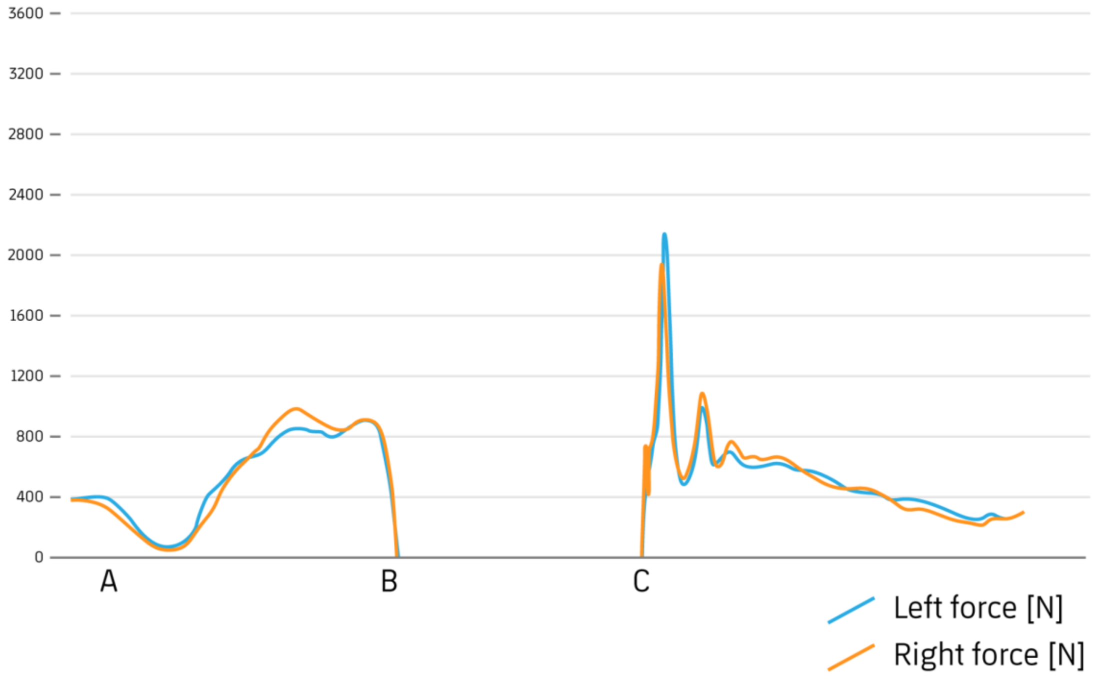
- Third law

When a force is exerted on an object, the object exerts a force that is equal to and opposite in direction of the original force. This is the basis of a force platform vertical ground reaction force (vGRF) measurement, reflecting the force applied by the athlete: as they apply force to the ground, the equal, reactive force (ground reaction force) in the opposite direction is measured.

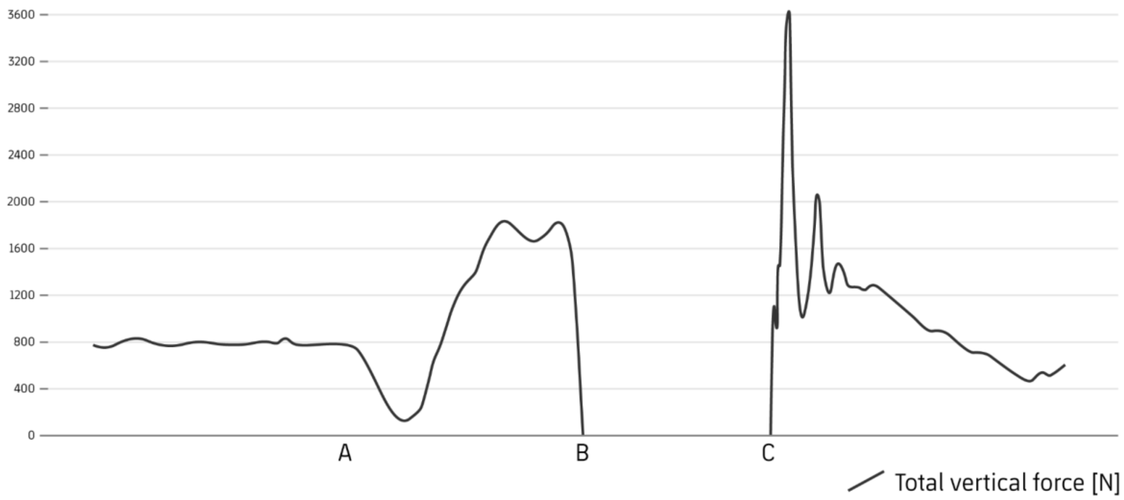
From raw force-time to velocity, power, displacement, and impulse –in a CMJ

Figures 3 and 4 show the kinetic (force) profile of a countermovement jump on a pair of vertical axis force platforms where the force data from each platform (left panel) is summed to generate a total vertical force-time curve (right panel). If using a single platform, the raw data would appear in the right panel. In either case, during a double leg CMJ performed on dual platforms, it is the total force (left + right) that is used in further processing to obtain velocity, power, and displacement, as these depend on having total system mass in contact with the platforms and entered into the calculations. This means that during a double-leg CMJ on dual-force platforms, velocity, power, and displacement curves are generated for the centre of mass but not for individual limbs. As one can see in figure 3a, during a bilateral jump on dual-force platforms, the left and right forces are obtained and combined to create a single vGRF trace (figure 3b). This allows simultaneous assessment of total bilateral variables and left and right outputs, and the calculation of interlimb force and impulse asymmetries.

Figure 3: Left, Right, total Vertical Ground Reaction Force.
3 A: Left and Right Ground Reaction Force



3 B: Total vertical Ground Reaction Force



A: Start of movement (downward phase); B: Take-off; C: Landing

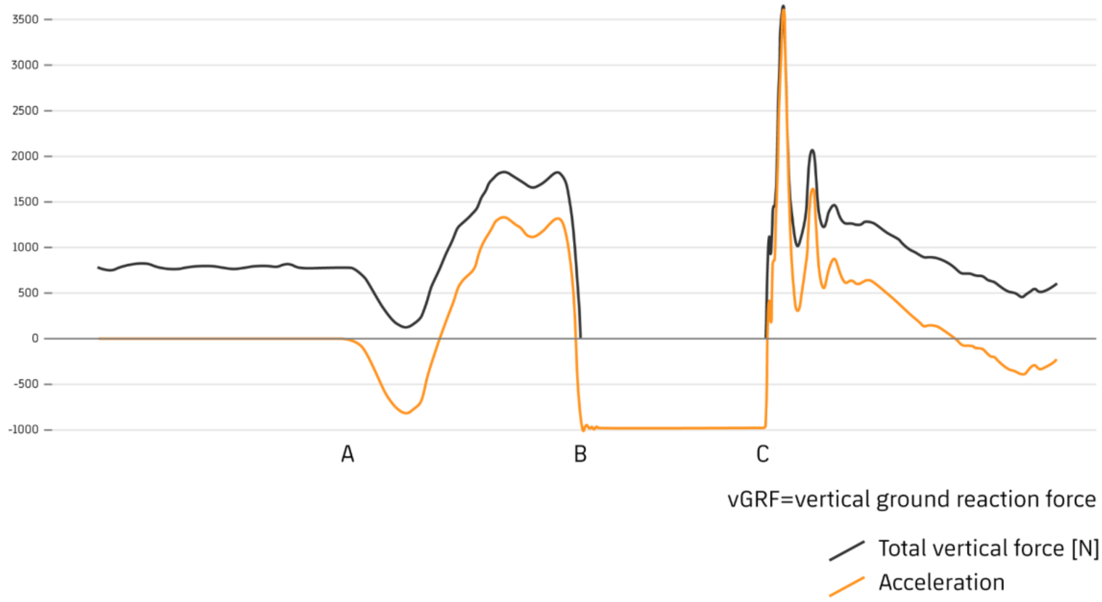
Source: authors own elaboration

Based on Newton's laws of motion, in a stepwise process the total vertical force-time profile, velocity-time, power-time, and displacement-time profiles are calculated, and from these, the variables used in athlete assessment are obtained. Note that the first step involves calculating the acceleration time by rearranging Newton’s second law of motion (force = mass * acceleration) and that mass is the athlete's body weight. This means that errors in the measurement of body weight are carried through the stepwise process and subsequent calculations such as velocity and power, with the accuracy of displacement, particularly affected (further explained below).

Inaccurate body weight is possibly the most common source of error in force platform jump testing in time-pressured squad/team testing in sports settings. The specifics of acquiring an accurate body weight value are discussed further.

Figure 5 shows the acceleration curve calculated from the force-time and measures body weight. Note that while it is necessary to calculate the acceleration-time profile as part of force-time data processing, it is rarely visualised in jump assessments or reported as a variable, since, as one can see, it parallels the force profile.

Figure 4: The vGRF and acceleration profile during a CMJ take-off and landing.



vGRF=vertical ground reaction force

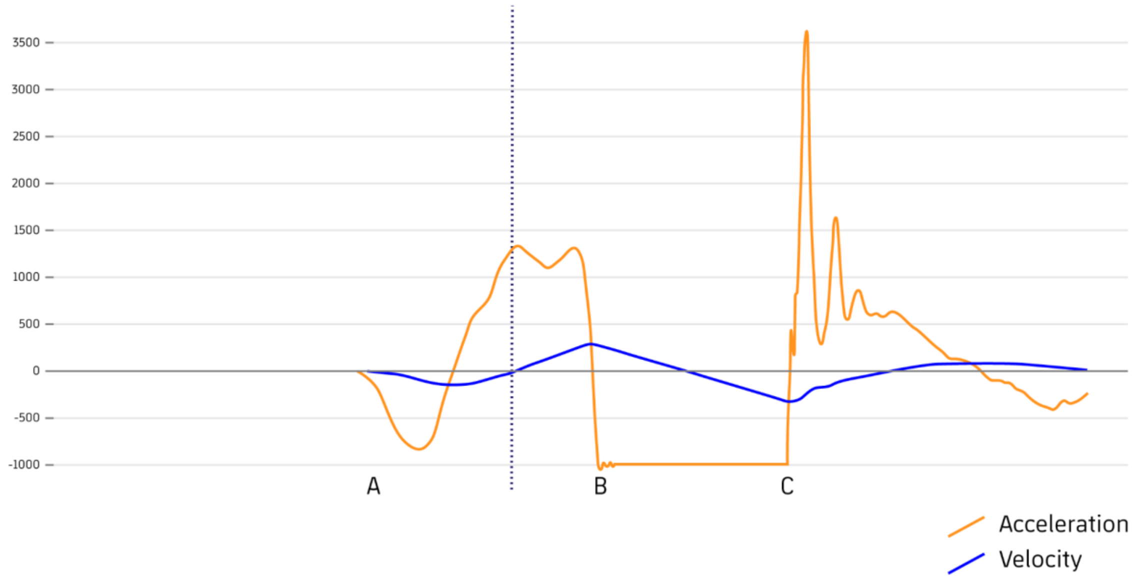
A: Start of movement (downward phase); B: Take-off; C: Landing

Source: authors own elaboration

The velocity-time profile

This is obtained from the acceleration-time profile, whereby acceleration is integrated to velocity with respect to time. Velocity is also equal to the sum of the resultant impulse divided by mass at any time point.

Figure 5: The acceleration and velocity profiles during a CMJ take-off and landing.



A: Start of movement (downward phase); B: Takeoff; C: Landing

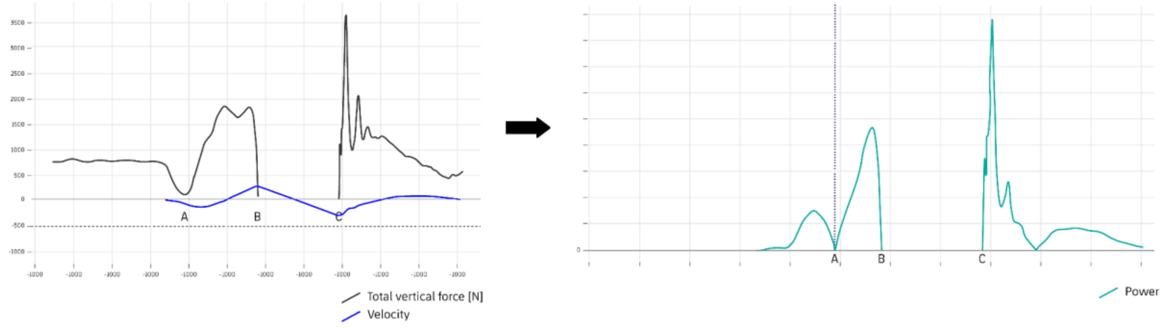
The vertical dashed line indicates zero velocity at the end of the downward ("eccentric")/beginning of the upward ("concentric") phase of the movement. Note that between the start of movement and the end of the downward phase, and on landing velocity is negative.

Source: authors own elaboration

The power-time profile

The power-time profile (see Figure 6) is the product of force and velocity at each time point. Peak concentric power, the highest instantaneous (meaning at a single point) power output is the second most commonly reported variable in jump testing after jump height itself. Other expressions of power such as, "peak and mean eccentric power" and "rate of concentric power development" are less commonly reported but have also been identified as relevant to monitoring and profiling (Cormie et al 2009; Cormie et al., 2010; Lonergan et al, 2022).

Figure 6: The product of the vGRF and velocity profile during a CMJ take-off and landing generates the power profile.



A: Start of movement (downward phase); B: Takeoff; C: Landing. Black dashed vertical line=zero velocity (the end of downward ("eccentric")/beginning of the upward ("concentric") phase.

Note that in 6B (right panel) the power profile during the downward ("eccentric") phase is actually negative, but in the figure shown as a positive value - this is for the purposes of visualisation.

Source: authors own elaboration

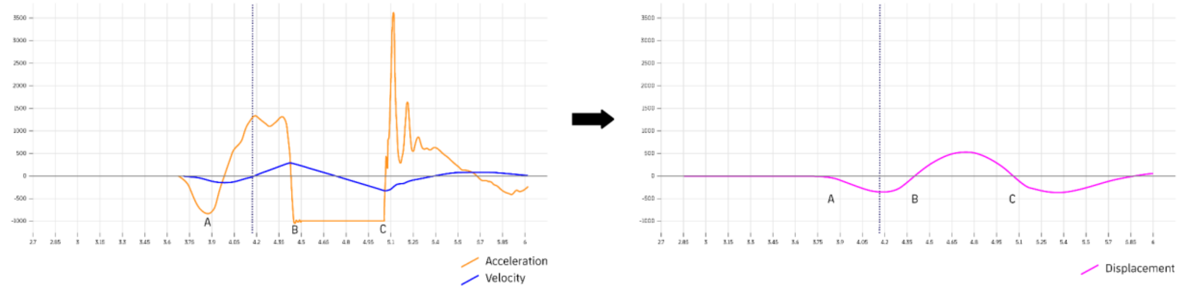
The displacement-time profile

The displacement-time profile represents the displacement or vertical position of the centre of mass of the jumper, with standing considered as zero and negative values representing the descent or downward phase of the countermovement jump. The displacement-time profile is obtained by the numerical integration of the velocity-time profile –or the double integration of the vGRF-time profile according to this equation:

$$\textbf{displacement} = \textbf{velocity} * \textbf{time} + (0.5) * \textbf{acceleration} * \textbf{time}^2$$

Figure 7: The displacement-time profile obtained from the acceleration and velocity time profiles

7 A: Acceleration and velocity-time profile **7 B: The displacement-time profile**

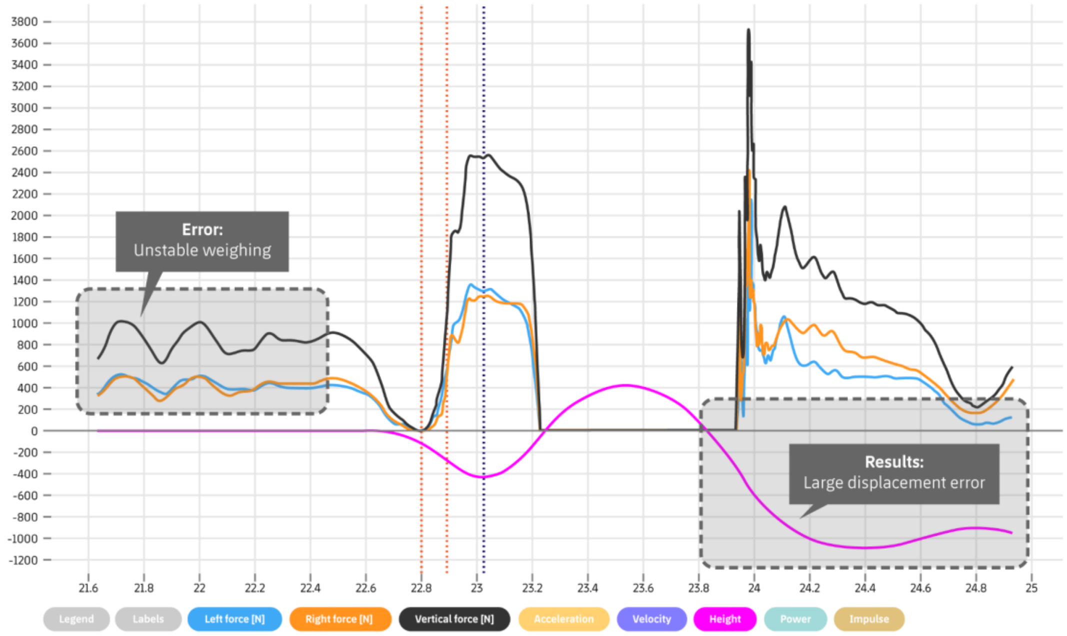


A: Start of movement (downward phase); B: Takeoff; C: Landing. Black dashed line=zero velocity (aligning with maximum negative displacement at the end of the downward phase).

Source: authors own elaboration

As mentioned above, displacement is particularly susceptible to errors due to inaccurate body weight measurement, and, because of multiplications within this equation, the accumulated error is magnified in this step (Vanrenterghem, 2001) making the displacement-time curve the curve most affected by errors. Large errors will manifest as a large obvious displacement error easily identified by inspecting the displacement curve (see Figure 9 as an example). In contrast, Figure 10 shows key events during a countermovement jump-land in a "good" displacement curve (defined on inspection as one in which the displacement of centre of mass at take-off is slightly above zero), which represents the additional centre of mass generated by plantar flexion (taking off on the toes), whereas the starting position is flat footed. There is a similar "offset" on landing. As the athlete comes back to starting position after flexion on landing, displacement returns to zero. Contrast this with the profile shown in Figure 9.

Figure 8: CMJ with large displacement error due to inaccurate body weight measurement.



Error:
Unstable weighing

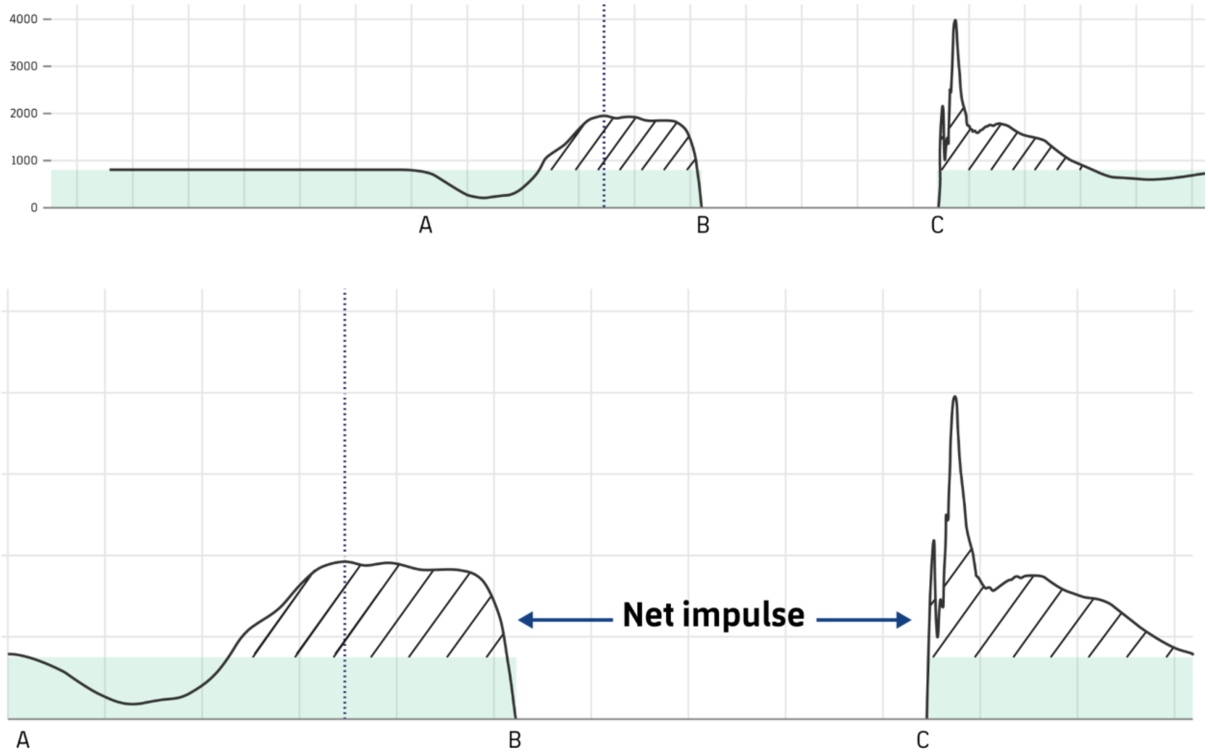
Results:
Large displacement error

Source: Vald Performance

Impulse

In addition to the generation of velocity, power, and displacement curves from which many variables are derived, the mechanical output; impulse –the product of force and time (force * time) representing overall force produced in a period of time or area under the force curve– is also calculated (see shaded areas in Figure 9). Figure 9 shows the complete force, velocity, power, displacement-time curve, and net impulse, from which many variables used are obtained and which can be analysed individually –comparing athletes or athlete groups or individuals over time.

Figure 9: Countermovement jump force-time profile and net impulse



Source: authors own elaboration

A: Start of movement (downward phase); B: Takeoff; C: Landing. Black dashed vertical line=zero velocity (the end of downward ("eccentric")/beginning of the upward ("concentric") phase.

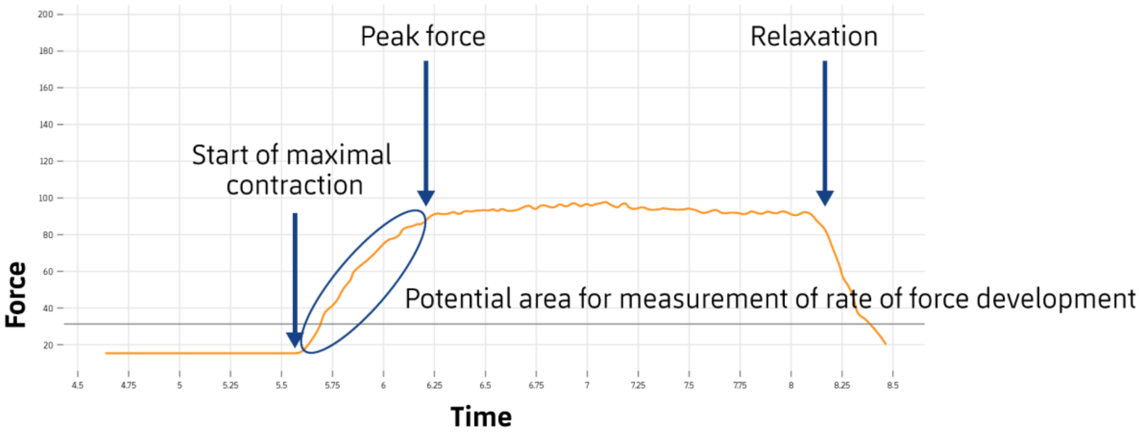
Impulse represents an accumulation over a specific time period, phase, or subphase rather than a curve or profile. As jump height is directly related to the resultant force performed on the centre of mass during the upward phase of a jump (SJ, CMJ or DJ), net concentric impulse (impulse above that due to the force generated by the athlete's body weight) is the principal determinant of jump height (see the figure below).

Equations which enable the estimation of concentric peak power from jump height and body mass/body composition are useful when force platforms are not available. However, they may have led to the erroneous belief that jump height is *determined* by peak power and that the two can be used interchangeably. Jump height is highly correlated with both average and peak power, but Linthorne (2021) highlights that the strength of the correlation is artificially inflated by the near-perfect correlation between jump height and the velocity at peak power and the correlation between velocity at peak power and velocity at take-off, which enters the impulse-momentum equation for estimating jump height (Linthorne, 2021).

The profiles generated during other dynamic tests are covered in other modules. As there is no movement in isometric tests, velocity, power and displacement curves are not generated;

therefore, we just consider the force-time curve, from which force, rate of force development and impulse variables are calculated, as well as potentially time to achieve a given level of force (see figure 10).

Figure 10: Sample isometric force-time curve showing components showing key events.



Source: authors own elaboration

Accurate body weight measurement is at the core of valid and accurate kinetic analysis, and underpins the reliability of a number of variables of interest

While body weight or segment weight may be of interest in isometric testing to express force relative to size., it is not critical to the accurate and valid determination of a host of other variables in the way it is in jump testing. In jump testing, the accurate determination of body weight affects the accuracy of the velocity, power, and particularly the displacement-time curves and variables derived from them. This can also impact the identification of the end of the eccentric/start of the concentric phase, as this is typically determined as either just prior to or just after zero velocity/maximum negative displacement, respectively. On this basis, it is important to be aware of typical causes of bodyweight errors and to be vigilant and focused on minimising these errors during assessments. Some of these are:

- *Zeroing*

The zeroing of platforms is recommended in most hardware/software systems prior to each athlete or series of assessments. This process recalibrates the sensors with no load being applied to the platform surface and, thus, the sensors themselves. During zeroing, which typically takes 1-2 seconds, in addition to no load being applied directly to the platforms, the practitioner should endeavour to ensure that there is no heavy footfall or vibration in the area around the platforms, particularly if the platforms are not on/in a concrete floor. In a gym setting, heavy weights dropped even meters away may be detected by the platforms offsetting the zero process. Note that heavy weights dropped during a recording can create force spikes within a jump or isometric test recording which may lead to false detection of events such as landing (if this impact occurs during flight) or a false peak force during a jump or isometric test.

- *Sensor calibration*

The precision and calibration of the force transducers can affect body weight measurement in two ways. First, while higher-quality sensors may be slightly more accurate than cheaper sensors (hence those embedded in cheaper hardware) at the time of purchase, the difference in the quality of sensors will have a larger influence over time. In essence, a lower quality and lower overload capacity sensor are more likely to drift from calibration over time as a given load is closer to maximum capacity; the degree to which the sensor and calibration deteriorate is dependent on the profile of use of the system (more specifically, the type of activities being performed on them). Jumps result in loads on sensors that are several times higher than the system is exposed to in isometric tests, principally due to impact on landing. Therefore, the frequency of recalibration or the potential for sensor damage depends on the interaction between the profile of use and the quality and overload capacity of the sensors. Most force platform systems need to be recalibrated by the manufacturers; verifying if the force reading reflects the true load, i.e., checking if it is still calibrated, can and should be done periodically (at a frequency determined by the factors described). However, most systems do not also allow the user to recalibrate them.

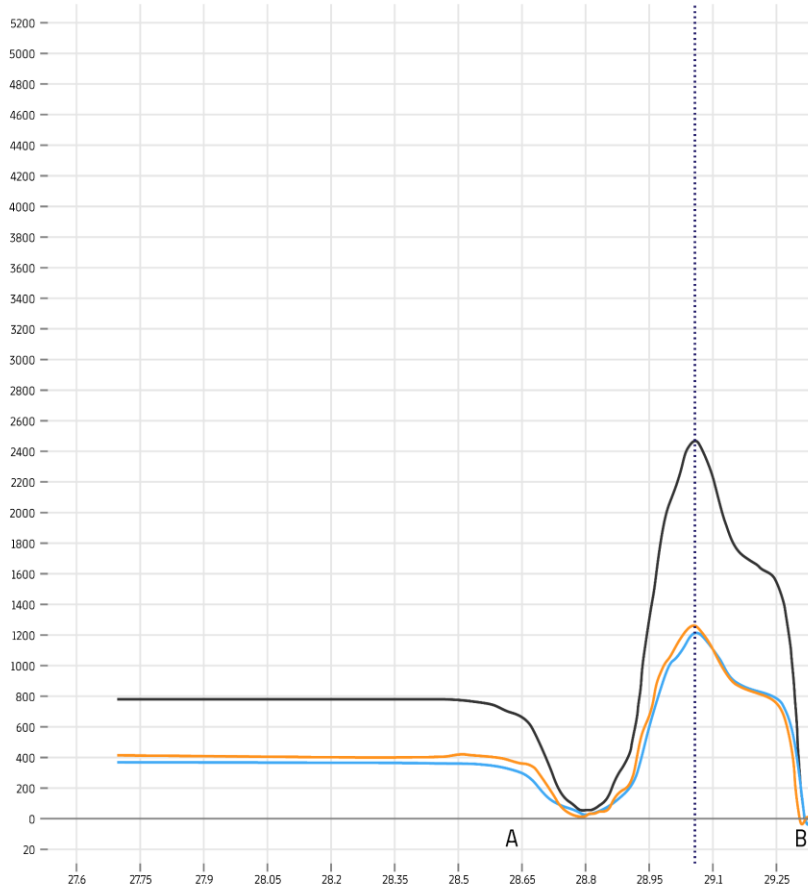
We now describe some aspects of protocol, environment, and instructions which optimise the precise measurement of body weight.

- *Quiet standing during body weight measurement*

As simple as the measurement of bodyweight and standing still for 2 seconds may sound, this is not always easily achieved in sports settings. However, the importance of achieving this cannot be understated: inaccurate body weight measurement and failure to achieve a brief period of quiet standing prior to descending into a double or single leg CMJ represent the practitioners biggest challenge to data quality.

There are several approaches to determining the body weight that may be entered into your bespoke (Excel/Matlab) force platform jump analysis or that is embedded in the proprietary software you might be using. Some software also has more than one option, or a back-up body weight calculation if bodyweight has not been measured prior to the test. Others have a fixed protocol which must be adhered to during body weight measurement. All of these methods depend on the athlete being still, upright with knees extended, and for dual platforms in an even stance across the two plates during the measurement period (typically, 1-2 seconds). Ensuring that not only the lower body is still, but also that the athlete is not moving their head, lifting their shoulders, or shifting their trunk for the period of bodyweight capture prior to testing and just prior to descending into the jump is not simple in a noisy gym with distractions including music and teammates talking, greeting, or bantering with the athlete on the platforms. You do not have to create a sterile environment to achieve this; in fact, as it is discussed, this may be detrimental to performance. However, a good bodyweight measure requires a few seconds of concentration not only on the part of the athlete, but also the practitioner, whose aim is to achieve a pre-jump trace similar to that of the one in figure 11 below, whereby both the total vertical force line and the left and right traces are flat. Note that, in figure 11, the athlete has a standing weight distribution that is asymmetrical but the left and right lines, whether equal or not, should remain parallel, leading up to the beginning of the countermovement. Further examples and details related to the visual inspection of bilateral CMJ and single leg CMJ force-time traces as well as the discussion of factors relevant to data quality are covered in other parts of the certificate.

Figure 11: Stable pre jump total vGRF, left and right force-time profiles.



A: Start of movement (downward phase); B: Takeoff

Dashed line = end of downward phase.

Source: authors own elaboration

A second aspect of validity/accuracy of measurement that is partially influenced by the practitioner relates to the treatment of the raw data delivered by the sensors. This includes:

- Sampling frequency of the force platforms
- Algorithms/thresholds used to detect/define events phases
- Data filtering

The maximum sampling frequency depends on the hardware purchased. Some software allows adjustment of sampling frequency below the maximum the hardware is capable of. This may be useful for consistency if one is concerned with comparing with data previously collected at a lower frequency; however, in general, one should use the highest frequency available (most commonly 1000 Hz). Frequency is important to accuracy and validity because the higher the frequency of sampling, the less likely a specific data point relevant to an event of interest will be missed. In jump-land activities, events/variables that could be affected by frequency include peak landing in a jump or the start of movement, the take-off or landing point. In isometric assessments, identifying the onset of contraction and, therefore, the measurement of “rate of force development is impacted by platform sampling frequency. Overall, therefore, frequency can influence the accuracy and the reliability of specific types of variables – peaks, rate of force development (Makaruk & Sacewicz, 2011) and temporal variables (i.e., durations), whereas means and impulses will be less affected.

Event detection/thresholds: Practical considerations

Whether using a proprietary system, an available code, or writing your own script, a decision has been made or will need to be made on how / when body weight used in the subsequent calculations is determined, and on which thresholds/calculations will be used to detect events - as there are a number of options. The specifics of some of these methods are described in module 2. When making these decisions, the practitioner should not only take into account what a lab-based research paper has concluded is the most reliable or accurate, but also consider factors related to the conditions under which your testing is being conducted. This includes noisiness of your environment, both in terms of auditory noise and likelihood of impacts in the same floor space (weights or other implements being dropped or jumps being performed in the vicinity) and in terms of the level of distraction within this setting and the body weight of the athletes typically being assessed. In essence, while narrow bands or low thresholds for events are preferable from a precision standpoint, and recommended, noisy environments, with a greater likelihood of distractions for athletes during assessments and heavier athletes, may challenge these and increase the likelihood of false start of movement detection. This may be identified and corrected post-hoc but creates an additional demand on practitioner’s time.

Some proprietary systems provide options for this within their settings. If there are such options or if you are defining this in Matlab or Excel, it is very important that your selection is then consistently used thereafter by all practitioners responsible for a group of athletes (i.e., one could use different settings for an adult versus a youth group). Changing body weight calculation, event detection, or data filtering settings can negatively affect your ability to interpret change over time as being due to neuromuscular responses. If there is an important reason to make changes, this should certainly be avoided during a monitoring cycle, that is, alterations, if necessary, should be left for the start in the next season/training phase. Alternatively, data already collected would need to be reanalysed with these new settings.

It is unreasonable to expect someone new (you or members of your performance or medical team) to force platform technology to become immediate experts in analysis or interpretation of kinetic data, nor is it necessary. However, it is critical that all staff involved in assessing athletes very rapidly do become experts in data **collection**. This expertise does not require expertise in biomechanics or even in the meaning and interpretation of kinetic variables; it depends on attention to detail, concentration, and consideration and diligent implementation of protocols. It requires that you ensure that all those who do the assessments are cognisant of the following:

1. Factors that can undermine quality of force platform data generally (as outlined above) and factors specific to data collection your workflow/environment - and identify means to avoid or minimise these. Factors include features of the equipment such as uncalibrated sensors, or platform location such as placement on uneven or inappropriate surfaces or noisy environments. Often, however, data quality issues can simply relate to inadequate or poorly communicated instructions, to the athlete’s following of instructions, to the practitioner’s lack of attention on the athlete during body weight measurement, or to the force-time trace prior to jumping. These factors challenge algorithms that define events and affect the calculation of variables of interest.
2. The specifics of protocol for the tests, related to the way they are set up (described in other modules) and to any modifications you make to these protocols are standardised, and well documented and communicated amongst all practitioners who may be tasked with running assessments.
3. The conditions surrounding athlete assessment - denoting influences on actual neuromuscular performance rather than data quality. Variations in these conditions across testing sessions, therefore, impact your ability to interpret change in variables over time or your confidence that the values you have collected truly represent the athlete’s capacity.

There are a number of acute conditions/practices which exert a significant or potentially important influence on performance in jump and isometric/other maximal strength tests *that the practitioner should be aware of and have a basic knowledge of the potential magnitude and direction of these effects on performance in these tests.*

Acute influences on jump and strength performance

Warm-up

Warm-up produces a number of physiological responses which enhance neuromuscular performance. While excess core temperature impairs performance, the effect of muscle temperature on performance is linear with a 1 °C increase associated with a 2 to 5% improvement in short-duration performance (Racinais & Oksa, 2010). Increased muscle temperature is associated with enhanced muscular strength and power, via several mechanisms including increased rate of metabolic reactions, increased conduction velocity of action potentials, increased extensibility of connective tissue and reduced muscle viscosity some of the relevant mechanisms cited (Racinais & Oksa, 2010).

Foam rolling

Many athletes incorporate foam rolling into their warm-up routines. A recent review and meta-analyses examined studies that evaluated strength & power performance within 10 minutes of rolling. The author's determined that this practice leads to trivial small reductions in jump height and strength but also concluded "that rolling does not induce considerable performance deficits" (Behm et al., 2020). In contrast, a recent study in university division 1 American Football showed a non-significant improvement in CMJ determined peak concentric power of 2.1% after rolling, alongside a non-significant increase of 0.8% following dynamic stretching (Tsai & Chen, 2021). The researchers also found the reverse for peak isometric force in knee extension and flexion, both showing a small non-significant decline after rolling (and dynamic stretching). A recent study in division 1 university volleyball players reported a significant 1.1 cm improvement in jump height in drop jumps performed at 2 minutes but not at 5 minutes after a rolling intervention (Tsai & Chen, 2021). Considering that small mean effects are reported in both directions following rolling, with potentially larger effects in a given individual, as well as potential time decay of positive effect and taking account this may be part of the athlete's warm-up routine, the emphasis for these assessments is maintaining consistency of rolling, or not, *within* individuals. When assessments are principally being implemented to detect change in variables in elite, adult athletes this supersedes a drive for consistency across individuals.

Cues/instructions

These are possibly the easiest and most obvious aspects of testing to standardise. However, it is not always the case that within an organisation the same cues/coaching instructions are delivered consistently over time and by the different practitioners responsible for running force platforms tests. Several studies have shown that different instructions can have significant effects on jump height and on kinetic variables (Mandic et al., 2016; Pérez-Castilla, 2019). The speed and depth of the countermovement, quantified by eccentric peak velocity (EPV) and countermovement depth (CMD), respectively, are "technical" characteristics of the jump that can be cued and acutely modified, but are also kinetic variables that need to be considered when interpreting trends in other commonly assessed metrics (Cohen et al., 2020; Pérez-Castilla et al., 2020). Because of this and the significant effect of the "jump as fast and high as possible" instruction on EPV and CMD and, in turn, other eccentric/downward phase variables compared to no cue or simply "jump as high as possible", standardisation of instructions is vitally important. No cue or "jump as high as possible" will contribute to less consistency of variables within the eccentric (Cohen et al., 2020) variables of interest. Similarly, in isometric testing cues around the speed at which force is applied will impact the ability to obtain valid rate of force development information in these assessments (Maffiuletti et al., 2016). The specific effects of cueing on kinetic and performance variables in the CMJ are covered in more depth in module 2.

Verbal encouragement and focus of attention

In research laboratory settings, verbal encouragement may be prohibited in order to standardise a factor which is known to influence performance, but, for obvious reasons (wording, level of encouragement, tone of voice, etc.), it is hard to standardise - and removed instead. However, encouragement and a competitive environment which includes feedback on athletes' performance during the testing session has a positive influence both on performance and on the reliability of results (Howarth et al., 2021). This may partly relate to the small positive effect of external focus of attention on jump performance in comparison to both an internal or no focus of attention (Makaruk et al., 2020). It is also suggested that numerical feedback during performance acts as a means to focus attention may contribute to the reliability of testing protocols (Tod et al., 2015). Interestingly, while maximum strength has been shown to be significantly and consistently enhanced by motivational and instructional self-talk, evidence for effects on jump performance are inconsistent (Tod et al., 2015). Nonetheless, a competitive environment with feedback may, therefore, support reliability by consistently directing the athlete's attention and help standardise psychological factors, and variability, which may otherwise contribute to variability in kinetics and performance (Edwards et al., 2008).

Time of day

Diurnal rhythms in human performance are well documented in CMJ, SJ, and DJ performance (principally using jump height and concentric peak power), isometric (peak force and rate of force development) and isokinetic strength. Performance in these and other short duration exercise tests have, with few exceptions, been shown to be higher in the afternoon/evening (peaking between 4:00 am and 8:00 pm). It is thought that circadian rhythms in core temperature (Tcore) –lowest at 6:00 am, peaking at 6:00 pm (Reilly, 1990)– play a major role in this effect. However, hormone levels, motivation and mood state, and neural and mechanical factors are also cited as contributors to the variations in jump and strength performance, which may not be entirely explained by the 2% variation in Tcore (Mirizio et al., 2020). Indeed, in elite Rugby 7's players West et al. (2014) observed a significant correlation (r = 0.78; P<0.001) between the increase in core temperature (1.3± 0.3%; and the increase in concentric peak power (5.1± 0.7%) in CMJ's performed at 5:00 pm compared to tests performed at 10:00 am. An r value of 0.78 suggests that around 50% of the variance in CMJ power can be explained by Tcore. Similar differences are reported in competitive male tennis players, with a CMJ height of 4.5% at 4:30 pm higher than at 9:00 am (López-Samanes et al., 2017).

Larger magnitude variations in isometric peak force across the day are reported. Some studies show mean differences of up to 30% between the morning and evening hours and as much as 41% in some individuals. In studies of knee extensor isometric strength, time of day effects have been reported on musculotendinous factors, including tendon stiffness, muscle fascicle length, and altered muscle architecture. These factors could potentially have a varying influence on tests with differing joint angles and on specific kinetics within the CMJ that have not been examined.

It is important to also be aware that evidence indicates that the time-of-day effect on jump performance or lower body muscle strength may be blunted in warm and humid environments, with studies showing no significant differences across the day in tests conducted in approximately 28C environments. A more extended warm-up prior to a series of CMJ has been shown to augment mean performance to levels observed following shorter warm-ups in the afternoon (Taylor et al., 2011). Again however, typically jump height and concentric peak power have been the outputs evaluated; therefore, it is not known whether other kinetic variables of interest are similarly affected. Furthermore, warm-up which raised Tcore to afternoon values has not consistently shown to also eliminate the evening deficit in isometric strength (Edwards et al., 2013).

Chronic training patterns

Several studies have shown that the typical diurnal rhythm in jump performance and isometric and isokinetic strength is attenuated when training is regularly performed in the morning. For example, large AM performance deficits in the CMJ, SJ and in knee extension peak force were significantly reduced in PE students after 12 weeks of morning resistance training (table 1) (Chtourou, et al. 2012).

Table 1: Diurnal differences in jump height and isometric peak force before and after 12 weeks of morning training

n=31	Baseline	12 weeks
Countermovement Jump (cm)	6.81 (2.33)	2.38 (3.76)
Squat Jump (cm)	8.93 (2.26)	1.79 (7.73)
Knee extension isometric peak force (N)	14.6 (2.43)	2.95 (3.75)

Values: mean performance at 5 PM – mean performance at 7 AM

Sourse: Adapted from The effect of training at the same time of day and tapering period on the diurnal variation of short exercise performances. H. Chtourou, et al. 2012. The Journal of strength and conditioning research, 26(3), 697–708. https://doi.org/10.1519/JSC.0b013e3182281c87

A 10-week morning strength training program resulted in a significant reduction in the AM deficit in isometric peak force in the knee extensors (Sedliak et al., 2008). However, such a substantial interindividual variation in this adaptation was observed, that while after the 10 weeks several subjects showed higher performance after the intervention than in the PM, others similar and some still performed poorly in the morning.

These findings indicate that one cannot assume that applying this approach will produce a homogenous response across a team peak in the morning and that, in terms of jump or strength assessments, practitioners cannot rely on the AM deficit being attenuated or reversed by training regularly at that time. This means that if the aim of the assessment is to determine an athlete's best performance in these tests, PM testing is likely to yield higher values. Furthermore, these data are not presented as an argument for not conducting assessments in the morning (in regular monitoring, in many sports, they are implemented at this time).

As in most instances the objective of testing is to identify meaningful change in individuals or groups, this data highlights the importance of implementing assessments at a consistent time of day and where this has not been possible**;** the direction and magnitude of the effects outlined above a change in these conditions are in important to be aware of and considered in interpretation of trend data. In simple terms, comparing performance from a test conducted in the AM with a previous PM would bias towards underestimation of positive adaptations/overestimation of fatigue, while comparing a PM test with a previous AM test would bias towards overestimating positive adaptations/underestimating fatigue. As always, consider the context/purpose of testing, as time of day is unlikely to affect interlimb asymmetries (since these effects are systemic), and as such that information is the principal purpose of a specific evaluation, then this becomes less critical.

Test timing relative to competition/high intensity training

In a similar way as described with respect to repeating tests at a similar time of day, comparisons of tests with very different conditions, in terms of the preceding days' loading, create similar biases. High-intensity activity comprising a substantial high-intensity eccentric/deceleration load within the previous 24-48 hours is likely to have a significant impact on specific performance and kinetic variables (Cormack et al., 2008; Gathercole et al., 2015; Cohen et al., 2021) and therefore on the interpretation of longitudinal trends of these variables. It is well established that competition/high-intensity training reduces neuromuscular performance in the subsequent 24-48 and potentially 72 hours. This “residual fatigue” has been mainly described in bilateral performance, but may also influence asymmetries (i.e., due to fatigue not being of equal magnitude in both limbs). As an example, when attempting to quantify the magnitude of improvement in neuromuscular performance improvement following pre-season training, the practitioner should attempt to the end of preseason test at least 48 and preferably 72 hours after a competition, since the positive adaptations may be masked by residual fatigue. On the other hand, when tracking week-to-week trends or residual fatigue in response to competition, comparisons should emphasise consistency in the time of assessment relative to competitive matches, such as match day +2 or +3 in football, Rugby or American football. Note however that these conditions and structure do not transfer to monitoring in professional basketball, baseball or ice hockey due to their competitive schedule (i.e., 3 or more games per week).

Contextualising and applying evidence around the effect of conditions on performance in assessment design and delivery

In monitoring, when aiming to identify potential change in neuromuscular status (i.e., to interpret changes or lack thereof between two timepoints or in a rolling average across weeks), it is essential to have a comprehensive knowledge of factors that may affect performance to enable you to critically evaluate the potential of these conditions to impact on the numbers you are collecting, even before applying statistical techniques to qualify potential changes as “meaningful” or “worthwhile”. Understanding those factors and the way your athlete’s context may impact on test results will provide you with the background to be able to make an informed decision when setting up a monitoring structure within elite sports. This will inevitably involve some trade-off between the “ideal” and practical/implementable conditions. In monitoring, embedding conditions that have the best chance of being repeatedly implemented and standardised across your organisation supersede the “best” condition. The degree of control you have over the conditions under which assessments are implemented will depend on a number of factors; global non-modifiable influences such as the sport, the level, the competitive schedule, the degree to which that schedule changes, and also some *potentially* modifiable team-/player- specific factors, such as player and management/coach buy-in to the process. The existing culture of in-season physical monitoring and your role within that environment of course delimits the implementation of assessments and the impact of data obtained and can change overnight due to changes in coaching staff. However, performance, S & C or medical staff can over time also drive changes in monitoring and assessment culture.

In circumstances where you are inheriting historical data or incorporating data from assessments which you did not implement, the aim is to also provide you with a framework to ask the important questions about the conditions under which that data was collected. While you cannot turn the clock back and change how tests were done, having this information will improve your interpretation of data and identify which factors in addition to the impact of competition, training, rehabilitation, and recovery strategies may have influenced the trends you are seeing, and potentially to improve the consistency of those conditions if appropriate.

Additional considerations for those at the beginning of their kinetic journey

Considerations in force platform purchase

When a budget is available for this type of equipment, stakeholders should consider whether more value is provided for the organisation by purchasing a single pair of triaxial platforms or for the same cost 3 pairs of vertical axis platforms. That is either an emphasis on:

1. developing the capacity to frequently and rapidly obtain assessments detailed neuromuscular performance and whole body (centre of mass) but not joint level biomechanical indicators on a larger number of athletes using standardised reliable jump and isometric assessments (with single or multiple single axis vGRF systems);

or

2. increasing the on-site capacity to obtain joint level biomechanical detail on a fewer number of athletes on a periodic basis (single triaxial + motion capture systems).

A number of factors should be taken into consideration in making such decisions:

- The volume of athletes that may need to be tested at one time and their time availability to perform these tests: is it a team sport, a multi-sport, or a military setting versus a setting where athletes are seen on an individual basis?
- The performance or rehabilitation questions being asked: the measurements being taken, as well as their potential to inform and influence decision making.
- The expectation/need for analysis of movement patterns and technical aspects of performance in contrast to underlying neuromuscular characteristics.
- Portability, the potential need for travelling with a system and the likelihood that system would need to move within a facility.
- The expertise of staff and time available to devote to analysis or access to an external consultant to support data acquisition analysis and interpretation.
- The potential and time frame for further budget to progressively expand testing capabilities or not i.e., purchase of triaxial platforms for future growth (in addition to single axis for current practice) because a budget is available that may not be in the future.

In sports settings, practitioners with a strong background and perspective on movement-based approaches to athlete evaluation and also new to force plates often have a natural interest in measuring sports-specific movements with the technology. While performing these types of evaluations with vGRF platforms is informative, due to the complexity of movement, axes involved, degrees of freedom, and technical contribution these assessments are more appropriately performed with triaxial platforms and motion capture –and, therefore, increased financial and time costs and expertise which need to be considered.

In the next module, the wealth of information describing athlete neuromuscular qualities and responses that can be derived from the force platform assessed CMJ is described, justifying its place as a core element of athlete strength and power monitoring processes

References

Behm, D., Alizadeh, S., Hadjizadeh, S., Mamdouh, M., Mahmoud, M. I., Ramsay, E., Hanlon, C. & Cheatham, S. (2020). Foam Rolling Prescription: A Clinical Commentary. *The Journal of strength and conditioning research, 34*(11), 3301-3308.

Chavda, S., Turner, A. N., Comfort, P., Haff, G. G., Williams, S., Bishop, C., & Lake, J. P. (2019). A Practical Guide to Analyzing the Force-Time Curve of Isometric Tasks in Excel. Strength and Conditioning Journal, 1. doi:10.1519/ssc.0000000000000507

Cohen, D. D., Burton, A., Wells, C., Taberner, M., Diaz, M. A. & Graham-Smith, P. (2020). Single vs double leg countermovement jump tests; not half an apple. *Aspetar Sports Medicine Journal,* 9, 34-41.

Cormack SJ, Newton RU, McGuigan MR, Doyle TL. (2008) Reliability of measures obtained during single and repeated countermovement jumps. Int J Sports Physiol Perform. Jun;3(2):131-44. doi: 10.1123/ijspp.3.2.131. PMID: 19208922

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *Journal of strength and conditioning research*, *23*(1), 177–186. https://doi.org/10.1519/JSC.0b013e3181889324

Chtourou, H., Chaouachi, A., Driss, T., Dogui, M., Behm, D. G., Chamari, K. & Souissi, N. (2012). The effect of training at the same time of day and tapering period on the diurnal variation of short exercise performances. *The Journal of strength and conditioning research, 26*(3), 697–708. https://doi.org/10.1519/JSC.0b013e3182281c87

Edwards, B. J., Pullinger, S. A., Kerry, J. W., Robinson, W. R., Reilly, T. P., Robertson, C. M., & Waterhouse, J. M. (2013). Does raising morning rectal temperature to evening levels offset the diurnal variation in muscle force production? *Chronobiology international*, *30*(4), 486–501. https://doi.org/10.3109/07420528.2012.741174

Edwards, C., Tod, D., & McGuigan, M. (2008). Self-talk influences vertical jump performance and kinematics in male rugby union players. *Journal of sports sciences*, *26*(13), 1459–1465. https://doi.org/10.1080/02640410802287071

Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. G. (2015). Comparison of the Capacity of Different Jump and Sprint Field Tests to Detect Neuromuscular Fatigue. *Journal of strength and conditioning research, 29*(9), 2522–2531. https://doi.org/10.1519/JSC.0000000000000912

Gomez-Bruton, A., Gabel, L., Nettlefold, L., Macdonald, H., Race, D., & McKay, H. (2019). Estimation of Peak Muscle Power From a Countermovement Vertical Jump in Children and Adolescents. *Journal of strength and conditioning research*, *33*(2), 390–398. https://doi.org/10.1519/JSC.0000000000002002

Güçlüöver, A., & Gülü, M. (2020). Developing a new muscle power prediction equation through vertical jump power output in adolescent women. *Medicine*, *99*(25), e20882. https://doi.org/10.1097/MD.0000000000020882

Harper, D. J., Cohen, D. D., Rhodes, D., Carling, C., & Kiely, J. (2021). Drop jump neuromuscular performance qualities associated with maximal horizontal deceleration ability in team sport athletes. European Journal of Sport Science, 1–12. doi:10.1080/17461391.2021.193019

Howarth, David J., Cohen, Daniel D., McLean, Blake D., & Coutts, Aaron J. (2021). Establishing the Noise: Interday Ecological Reliability of Countermovement Jump Variables in Professional Rugby Union Players. Journal of Strength and Conditioning Research, Publish Ahead of Print.

Linthorne, N. P. (2021). The correlation between jump height and mechanical power in a countermovement jump is artificially inflated. *Sports biomechanics*, *20*(1), 3–21. https://doi.org/10.1080/14763141.2020.1721737

Lonergan BM, Price P, Lazarczuk SL, Howarth DJ, Cohen DD. (2022) A Comparison of Countermovement Jump Performance and Kinetics at the Start and End of an International Rugby Sevens Season. The Journal of Sport and Exercise Science Vol. 6, Issue 2, 79-89

López-Samanes Á, Moreno-Pérez D, Maté-Muñoz JL, Domínguez R, Pallarés JG, Mora-Rodriguez R, Ortega JF. (2017). Circadian rhythm effect on physical tennis performance in trained male players. *Sports Sci. Nov;35(21):2121-2128. doi: 10.1080/02640414.2016.1258481*.

Loturco, I., D'Angelo, R. A., Fernandes, V., Gil, S., Kobal, R., Cal Abad, C. C., … Nakamura, F. Y. (2015). Relationship Between Sprint Ability and Loaded/Unloaded Jump Tests in Elite Sprinters. Journal of Strength and Conditioning Research, 29(3), 758–764. doi:10.1519/jsc.0000000000000660

10.1519/jsc.0000000000000660

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *European journal of applied physiology*, *116*(6), 1091–1116. https://doi.org/10.1007/s00421-016-3346-6

Mandic, R., Knezevic, O., Mirkov, D. & Jaric, S. (2016). Control strategy of maximum vertical jumps: The preferred countermovement depth may not be fully optimized for jump height. *Journal of Human Kinetics, (52)*, 85-94. https://dx.doi.org/10.1515%2Fhukin-2015-0196

Makaruk, H., Starzak, M. & Marak Porter, J. (2020). Influence of Attentional Manipulation on Jumping Performance: A Systematic Review and Meta-Analysis. *Journal of Human Kinetics, 75*, 65-75. https://dx.doi.org/10.2478%2Fhukin-2020-0037

Makaruk, H. & Sacewicz, T. (2011). The effect of drop height and body mass on drop jump intensity. *Biology of Sport, 28*(1). http://dx.doi.org/10.5604/935873.

Meylan CM, Nosaka K, Green J, Cronin JB. (2011) The effect of three different start thresholds on the kinematics and kinetics of a countermovement jump. J Strength Cond Res. Apr;25(4):1164-7. doi: 10.1519/JSC.0b013e3181c699b9.

Mirizio, G. G., Nunes, R., Vargas, D. A., Foster, C., & Vieira, E. (2020). Time-of-Day Effects on Short-Duration Maximal Exercise Performance. *Scientific reports*, *10*(1), 9485. https://doi.org/10.1038/s41598-020-66342-w

Owen NJ, Watkins J, Kilduff LP, Bevan HR, Bennett MA.(2014). Development of a criterion method to determine peak mechanical power output in a countermovement jump. J Strength Cond Res. Jun;28(6):1552-8. doi: 10.1519/JSC.0000000000000311.

Pérez-Castilla, A., Weakley, J., García-Pinillos, F., Rojas, F. J., & García-Ramos, A. (2020). Influence of countermovement depth on the countermovement jump-derived reactive strength index modified. *European journal of sport science*, 1–11. Advance online publication. https://doi.org/10.1080/17461391.2020.1845815

Racinais, S. & Oksa, J. (2010). Temperature and neuromuscular function. *Scandinavian Journal of Medicine & Science in Sports*, *20*(3), 1–18. https://doi.org/10.1111/j.1600-0838.2010.01204.x

Reilly T. (1990). Human circadian rhythms and exercise. *Critical reviews in biomedical engineering*, *18*(3), 165–180.

Sahrom SB, Wilkie JC, Nosaka K, Blazevich AJ (2020) The use of yank-time signal as an alternative to identify kinematic events and define phases in human countermovement jumping. R Soc Open Sci. 2020 Aug 26;7(8):192093. doi: 10.1098/rsos.192093.

Sayers, S. P., Harackiewicz, D. V., Harman, E. A., Frykman, P. N., & Rosenstein, M. T. (1999). Cross-validation of three jump power equations. *Medicine and science in sports and exercise*, *31*(4), 572–577. https://doi.org/10.1097/00005768-199904000-00013

Sedliak, M., Finni, T., Peltonen, J., & Häkkinen, K. (2008). Effect of time-of-day-specific strength training on maximum strength and EMG activity of the leg extensors in men. *Journal of sports sciences*, *26*(10), 1005–1014. https://doi.org/10.1080/02640410801930150

Taylor, K., Cronin, J. B., Gill, N., Chapman, D. W., & Sheppard, J. M. (2011). Warm-up affects diurnal variation in power output. *International journal of sports medicine*, *32*(3), 185–189. https://doi.org/10.1055/s-0030-1268437

Tod, D., Edwards, C., McGuigan, M., & Lovell, G. (2015). A Systematic Review of the Effect of Cognitive Strategies on Strength Performance. *Sports medicine (Auckland, N.Z.)*, *45*(11), 1589–1602. https://doi.org/10.1007/s40279-015-0356-1

Tsai, W., & Chen, Z. (2021). The Acute Effect of Foam Rolling and Vibration Foam Rolling on Drop Jump Performance. *International Journal of Environmental Research and Public Health, 18*(7). https://doi.org/10.3390/ijerph18073489

Vanrenterghem, J., Nedergaard, N., Robinson, M. & Drust, B. (2017). Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. *Sports Medicine, 47*(5), 1-8. https://link.springer.com/article/10.1007/s40279-017-0714-2

West, D. J., Cook, C. J., Beaven, M. C. & Kilduff, L. P. (2014). The influence of the time of day on core temperature and lower body power output in elite rugby union sevens players. *Journal of Strength and Conditioning Research, 28*(6):1524-1528. https://doi.org/10.1519/jsc.0000000000000301