Module 2. The CMJ (countermovement jump) as a core test

This module aims to develop your knowledge and understanding of the kinetics and variables derived from the bilateral (double leg) countermovement. The CMJ is one of several kinetic assessments that you might implement in a sports or clinical setting–many of these others are covered elsewhere in the certificate. However, the CMJ is the most commonly implemented jump test and, while other assessments may be introduced, it should remain a core test in assessing the healthy and rehabilitating athlete. There are both practical and scientific justifications for this assertion. From a scientific perspective, of the jump tests used in athlete assessment, the CMJ has the largest evidence base supporting the use of both performance (jump height) and variables derived from a comprehensive kinetic analysis in the profiling and monitoring applications. The eccentric, concentric and landing kinetics generated in the force platform assessment of the CMJ, which represent diverse neuromuscular characteristics of the athlete, provide the largest information gain relative to that obtained by performance output (i.e., jump height) data alone.

CMJ kinetics provide insights into the underlying neuromuscular performance qualities that contribute to the output of that jump task and can reveal large differences between athletes and across sports. Table 1a shows an example of this information gain, whereby substantial differences in the kinetic variables can be observed in two elite athletes with very similar jump heights.

Table 1a. CMJ height and -kinetic variables in two elite athletes

	Footballer	Olympic Weightlifter
Jump Height (Flight Time) [cm]	**55**	**54**
Flight Time: Contraction Time	1.11	0.84
Con Peak Power/BM [W/kg]	67.0	80.3
Eccentric Peak Power/BM [W/kg]	32.8	9.0

Source: Prepared by the author.

In other words, in contrast to the substantial added value of kinetic variables in the CMJ relative to jump height alone, there is currently far less evidence showing substantial additional insights gained (from a performance profiling or monitoring perspective) from analysis of kinetic data in the drop, squat or single leg jump compared to the jump heights/contact times obtained in those tests through other technologies. Further examining their profiles (table 1b), it is evident that while there are large differences between these two athletes in certain variables such as concentric and eccentric power and eccentric

deceleration duration, values in other values are identical or show much smaller differences, such as concentric peak force, concentric duration. This example also demonstrates that not all kinetic variables align or demonstrate the same qualities. Hence the value of examining an adequate range of variables when using the CMJ in profiling.

Table 1b. CMJ- height and kinetic variables in two elite athletes

	Footballer	Olympic Weightlifter
Downward ("eccentric") phase		
Countermovement depth[cm]	31.5	30.6
Eccentric Peak Velocity [m/s]	-1.66	-0.83
Eccentric Deceleration phase duration [ms]	116	195
Eccentric Deceleration RFD [N/s/kg]	172	79.0
Upward ("concentric") phase		
Concentric peak force [N/kg]	28.7	30.0
Concentric Peak Velocity [m/s]	3.2	3.42
Concentric Impulse-100ms [Ns]	151	120

Source: Prepared by the author.

In senior high-performance or professional settings, particularly in team sports, it is not generally feasible to routinely deliver frequent extensive test batteries. In this context, the CMJ serves to provide as much information as possible about the neuromuscular qualities of the athlete with minimum demand on the athlete–in terms of loading demand, technical skill and familiarization required, and time spent performing it. Importantly, in terms of integrating competitive cycles as part of regular monitoring, CMJs have not been shown to be a fatiguing test, indeed they are often included in warm-up and activation sessions, as there is evidence for post-activation potentiation following double leg countermovement jumps

(DL-CMJ). Note that the concept of minimum assessment dose or demand for maximum information gain is most pertinent to the professional or senior athlete–in youth development, there may be more latitude in implementing testing and a wider range of qualities can more easily be assessed using a more extensive range of neuromuscular and movement/sports specific tests. Furthermore, given the greater space for conditioning, a broader range of conditioning may be delivered, and the needs for which and results of these programs may also be more extensive.

There are two important caveats to the notion of greater information gain moving from CMJ jump height to CMJ kinetics compared to single-leg jump height or drop jump height, contact time, and RSI (reactive strength index) to kinetics in these tests. This is partly because in comparison to the body of work on CMJ kinetics, far fewer studies (i.e., Harper et a., 2022; Pedley et al., 2022a, b; Lloyd et al, 2022) have examined the potential added value that vGRF kinetic analysis can provide in other common jump tests such as the drop jump - that is beyond examining peak landing force in this test, for which there is a large body of work.

While in the healthy athlete, flight, and contact times derived from the drop jump appear to be adequate from a performance profiling (Harper et al., 2021) and load response monitoring perspective (Hamilton, 2009; Schmitt et al., 2015), double leg drop jump kinetic asymmetries are well documented and provide important additional information relevant to injury risk screening, post-injury residual deficits (Paterno et al., 2007), and potentially ACL recurrence (King et al., 2018), and therefore also in rehab and RTS (return to sport) following this injury (discussed further in “Injury and Rehabilitation Kinetics and Kinematics” course).

There are a host of practical and contextual considerations which underpin the denomination of the CMJ as a core test, but it is not necessarily the only test within the kinetic profiling and monitoring. From an integration or athlete buy-in perspective, athletes are very often familiar with the test albeit usually with a contact mat, optical device, or other means of testing, if not in regular monitoring, then at least as part of assessment during youth development pathways or in preseason/periodic testing approaches. Note, while these considerations can be defined as practical, may affect the translation of the evidence base supporting the use of the dual-platform CMJ tool into the applied setting. For example, the greater familiarity with a lower technical demand of the CMJ relative to other tests such as single leg jump (SLJ) (Cohen et al., 2020) and drop jump (Gathercole et al., 2015). In a comparison of interday reliability between (double leg) CMJ, squat jump (SJ) and DJ performance and kinetic variables, Gathercole et al. (2015) reported a significantly higher coefficient of variation in the DJ (indicating lower reliability) compared to CMJ and SJ. The better inter-trial and inter-day reliability of kinetic variables - reduced “noise”– combined with significant responses - “signal” underpins an increased potential for detecting a meaningful change. Another advantage of the DL-CMJ in terms of athlete buy-in to regular (especially, in-season) testing, is the perception of its low loading demand relative to tests, such as the DJ SLJ. Indeed, this is not simply perception; drop jump landings generate a knee loading demand than a DL-CMJ landing of the same height (Harry et al., 2018) and the relative loading demand of a single leg

take-off is greater than that of the DL-CMJ (Harry, et al., 2018). A consequence of this is a greater willingness to perform more frequent assessments, and testing during the competitive season, which translates to an increased likelihood to detect anomalous trends. In rehabilitation, there are a number of contextual and practical considerations around the use of the CMJ which are discussed in the "Injury and Rehabilitation Kinetics and Kinematics" course.

The practitioner should also be fully cognisant of both the kinetic data and performance outputs obtained from other tests. As such, depending on the performance/injury question being asked, the athlete/demands of their sport/position, or specific neuromuscular quality of interest, the practitioner can judiciously select these additional tests, and how, whether they fit into strength and power diagnostic evaluations across a team or with specific individuals, to further inform decision-making. Nonetheless, with access to force platforms, practitioners should first master CMJ data acquisition, supporting the highest levels of reliability and validity possible within their environment. Then develop a thorough understanding and ability to interpret a limited number of kinetic variables derived from the test. A more comprehensive understanding of the extent and limits of the information the CMJ can provide, combined with a specific performance or injury-related question, will be the basis for the selection of additional tests using force platforms or not. It is important to have clarity on what specific information is being gained by these as inherent to the delivery of a larger battery of tests is an increased demand on the athlete and on staff resources.

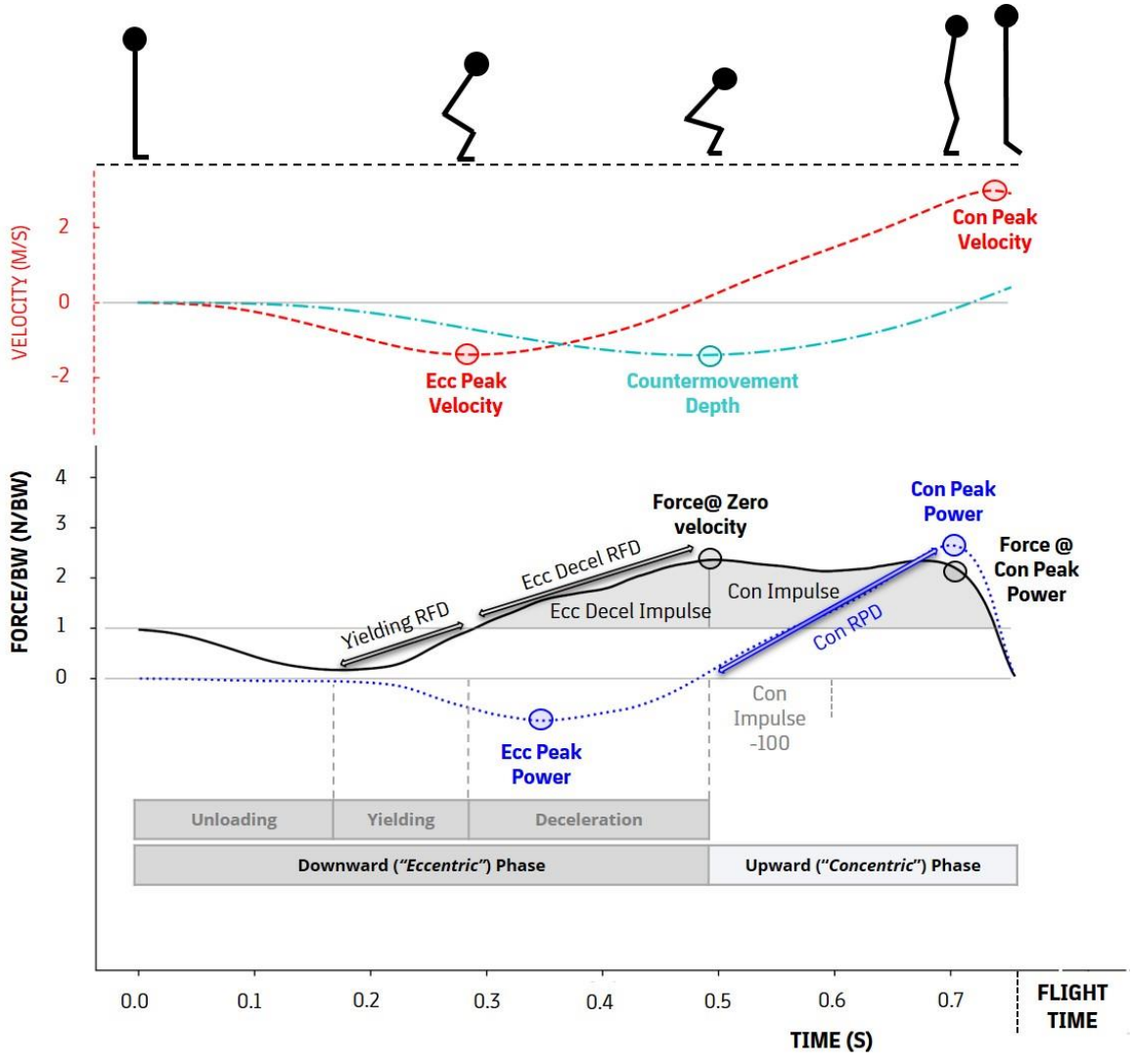
Variables/Metrics

In module 1 of this course, you were familiarised with the stepwise process by which the raw force-time curve, velocity-time, power-time, and displacement-time profiles were derived, and impulse was calculated from a CMJ performed on single or dual force platforms. Here, we provide a comprehensive description of the resultant figure (figure 1) with phases and approximate body/joint positions overlaid to identify these with phases and subphases described. Using variables obtained from these traces is the principal and the most common approach to quantify neuromuscular performance or change thereof using the CMJ in high-performance settings. Broadly, CMJ kinetic variables or "metrics" represent:

- Discrete points; a value obtained from a single point on one of the curves (i.e., force, power, velocity or displacement) that aligns with a specific event or is a local (phase-specific) maxima or minima within one of the curves. For example, concentric peak force, velocity or power, minimum force, force at concentric peak power, force at zero velocity, maximum countermovement displacement, or displacement at landing peak force.
- Averages (force or power) or summed (impulse) values; across a phase, such as concentric mean force and concentric impulse.

- Averages or summed values; across a specific subphase or time-constrained “epochs”. For example, the first 100 m of the concentric phase: concentric impulse-100 or mean eccentric deceleration force
- Rates/slopes; are calculated over phases, subphases, or specific epochs of the force or power curve. For example, eccentric deceleration rate of force development, and concentric power slope. Temporal or durations; -phase or sub-phase durations or time are taken to reach a specific event or maxima or minima. For example, concentric duration, eccentric deceleration duration, time to peak force or peak power.
- Ratios; include performance output relative to kinetics for example Reactive Strength Index Modified (Jump Height: Contraction time), or to describe kinetics across phases such as Eccentric: Concentric force or duration ratios, or within-phase kinetic calculations such as stiffness (change in force: change in centre of mass displacement).

Figure 1: Force, Velocity, Power, Displacement-time traces, phases and selected variables.



From: Adapted from Cohen & Kennedy 2021.

In addition to analysing and comparing variables between or within athletes, the qualitative visualization and the quantitative statistical analysis of the force-time, velocity-time, power-time, displacement-time or the force-displacement, velocity-displacement traces by overlaying consecutive measurements in an individual or another athlete or group can also be used to characterize jump performance or identify change over time. To some, these raw curves are intimidating, however, you will need to become comfortable with them for your use and so you can explain them to colleagues and athletes. You will find that some colleagues and athletes respond better to these types of visualizations than a page of numbers or graphs), in other words, it is useful to have options in your toolbox in terms of communicating kinetic data. Waveform analysis and some of these other approaches are discussed later in this module.

It is important that the practitioner develops a good vocabulary of variables and their definitions and some grasp of where and how they are derived. While traditionally, the majority of force platform articles have only reported jump height and concentric peak power, in a 2016 review, Claudino et al. (2017) identified 63 unique variables in the literature but highlighted that 46 of these variables have only been reported on once or twice. Eagle et al. (2015) highlighted that the methods for CMJ phase identification for the vertical jump are not consistent across the literature and that a substantial number of studies reporting force-time CMJ variables did so without identifying the phase they are derived from.

In addition to existing variations in terminology across research and proprietary software, including for the basic phases of the jump, variables will continue to enter the literature and practice. It is certainly not necessary to report on and monitor all of these, but taking ownership of one's data and understanding how variables might be used to understand athlete status and progress means going beyond a variable name and gaining clarity on **where** it is derived from and **how** it is derived. Eagles et al. (2015) concluded that the great variability in these variables in the literature makes what we can really extract from such research questionable. However, armed with the ability to understand the description of a variable or a figure in the methods section of a paper, you can determine what phase or subphase was being assessed and extract useful data from the research even if the terms used or definitions do not align with that used currently. It is worthwhile developing the ability to do this as these studies may have important findings that you would otherwise not be able to interpret.

Jump-land Phases: terminology and definitions

Note that the three main phases of the CMJ during which the athlete is in contact with the platforms are defined principally by displacement of the centre of mass (COM). The downward phase begins at the start of movement (different methods are used to identify start of movement - summarised below) and ends at maximum negative displacement during the take-off phase (also termed maximum countermovement depth), followed by the upward phase which ends at the highest point of COM displacement before the athlete leaves the

platforms (above that of the flat-footed start of movement - as the athlete leaves the platform plantar flexed), and the landing phase. In much of the research, and in some force platform software, the CMJ is divided into 3 phases: eccentric (or braking), concentric (or propulsive), and landing. However, recently, not only has there been a proliferation of variables and terminology used to describe these phases and subphases in the scientific literature (Eagles et al., 2015), but it was also highlighted that there are 3 common methods used to identify phases and noted that processing a sample raw data set produced different results with each approach.

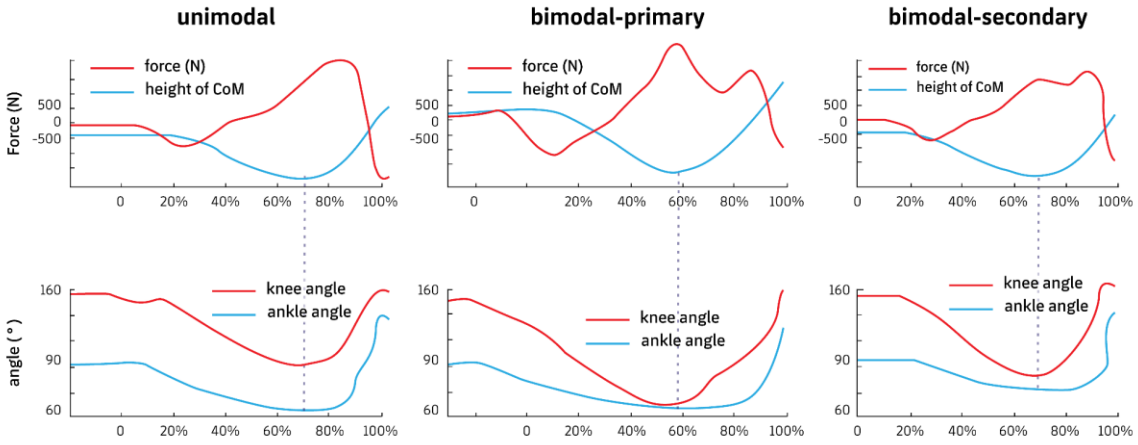
In this module, we will overview the different approaches, but emphasize the description of the phases and variables to ensure that you are not confused by terminology differences in research, textbooks, software, or other sources of information. Older research and texts, as well as terminology embedded in variable names, generally refer to variables within the downward phase as “eccentric” (i.e., eccentric peak power, eccentric duration) and within the upward phase as “concentric” (i.e., concentric peak power, concentric peak velocity). As variables within these phases have retained this nomenclature in some software and literature, we also retain the use of eccentric and concentric prefixes for variable names within this certificate.

The practitioner’s ability to interpret existing and future research and to shift between software systems confidently depends on the ability to recognize what sections of the jump are referred to by the various terms employed, which means developing an understanding of how phases are defined, what occurs is each phase, and also how variables within each phase are calculated. Note that the nomenclature differences are principally within the bilateral *CMJ* literature and software, but some of this discussion is also relevant to other jumps, particularly those which involve a countermovement (such as the single-leg CMJ and single and double-leg drop jump). Armed with this information, you will also be able to identify from the methods section of a research paper what is meant by a particular variable and how a phase has been defined and therefore be capable of critically evaluating new information or variables and potentially transferring this into their assessment and monitoring processes. The most common phase and subphase terms and definitions within the relevant literature and software used in sports settings are outlined below, with most of the discrepancies in terminology related to the “eccentric” or downward phase.

The first terminology discrepancy to be aware of is the move away from the use of eccentric and concentric phases in the literature to the use of terms “downward” and “upward” or “propulsive”, respectively. The two phases of the overall take-off phase (start of the movement to toe-off) are defined by the centre of mass displacement direction (i.e., descent or ascent) or velocity (positive or negative), not by actions at individual joints. In simple terms, the end of the “eccentric” phase and the beginning of the “concentric” phase is identified as the instant before and after maximum (negative) displacement which coincides with the deepest position at the end of the countermovement. This is the basis of this shift to downward and upward terminology relates to the fact that during the “eccentric phase” of

the jump, the individual's muscles involved in the jump which cross the hip, knee, and ankle joints, are not all lengthening throughout this phase or all shortening during the "concentric phase" (Bobbert & Schenau, 1988). Similarly, figure 2 showing synchronized kinetic-kinematic data during the CMJ (Sahrom et al. 2020) demonstrates that while maximum knee flexion aligns very well with maximum negative COM displacement, peak ankle dorsiflexion has not yet been attained.

Figure 2: Centre of mass displacement at downward (*eccentric*) to upward (*concentric*) phase transition with knee and ankle joint angles



Source: Adapted from figure 4 Sahrom et al. 2020

The dashed line shows maximum COM displacement (height of COM) which defines the eccentric to concentric transition in 3 types of jump waveform (discussed below) and the knee and ankle joint angles at this time point. Note the alignment of max COM displacement with maximal knee, but not ankle flexion. Hence the move to the use of downward (or countermovement) and upward (or propulsive). We refer to the combination of the downward and upward phase as the take-off phase to distinguish it from the landing phase. The term "contact phase" has also been used (Warr et al., 2020).

Below we describe the phases and subphases used in research and software systems, with the variables and terminology used. For metrics commonly expressed relative to body mass (kg), an example of such values but note that absolute (raw) values may also be reported for these metrics.

Variable types and units

- *Durations (or "time") or time to an event* seconds or milliseconds (e.g., an eccentric duration or time to peak power of 0.450 s or 450 ms,)
- *Force:* Newtons or Newtons (e.g., a concentric peak force of 21.7 N/kg).

- *Rate of force development (change in force / change in time):* Newtons per second (e.g., an eccentric RFD 54.5 N/s).
- *Impulse*:* Newtons x seconds (e.g., a concentric impulse of 242 Ns).
- *Velocity:* metres per second (e.g., a concentric peak velocity of 2.55 m/s or an eccentric peak velocity of -1.57 m/s**).
- *Power:* Watts or Watts/kg (e.g., a concentric peak power of 71.5 W/kg or eccentric peak power of 22.7 W/kg**).
- *Rate of power development (change in power / change in time):* W/s/kg (e.g., concentric rate of power development or concentric power slope of 210 W/s/kg).
- *Displacement:* meters or centimetres (countermovement depth = 34.5 cm***).

*When reporting bilateral (from the total vGRF trace) impulse, "net" impulse is generally reported –which means that the contribution of body weight is subtracted (as illustrated in module 1). When reporting left and right impulse or impulse asymmetries absolute values for each limb (or these values - 50% of body weight) are used.

**As in the downward phase velocity is negative, "eccentric" velocity and power (force x velocity) metrics are expressed with a negative sign.

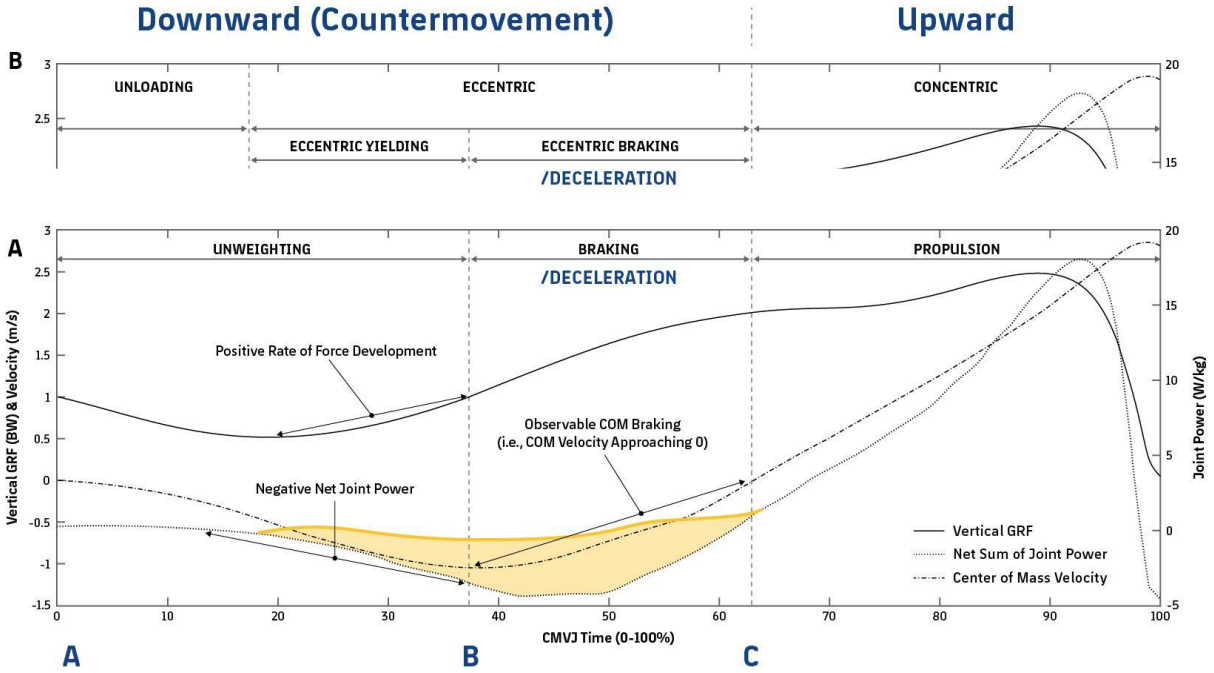
*** CM depth has also been scaled to athlete's height (Chalitsios et al., 2019).

Downward ("eccentric") phase and subphases

In landmark work in the field that demonstrated that acute, residual, and chronic responses to load were revealed with a comprehensive CMJ kinetic analysis, but not by assessing jump height alone (Gathercole et al., 2015), the CMJ take-off phase was simply divided into an eccentric phase or "eccentric duration", defined as beginning at the start of movement and ending at zero velocity or maximum negative displacement. As highlighted, there are a number of ways to identify this start of movement, but they all conceptually aim to define the beginning of the descent into the countermovement.

The early work of Komi & Bosco (1978) however adopted a subdivision within the downward phase, referring to the period after the onset of movement during which vGRF falls below bodyweight as the "unweighting" phase, and only defined the period after vGRF returns to this value until the beginning of the concentric phase as "eccentric phase". This latter, "eccentric" subphase is termed "eccentric deceleration" in more recent work (Jakobsen et al., 2012) (figures 3 and 4)–as it begins at the point of maximum negative velocity ("eccentric peak velocity") and the return of vGRF to the body weight value. It is important to note however that some research groups and software use the term "braking phase" instead of "eccentric deceleration phase".

Figure 3: Approaches to jump phase (downward/*eccentric* and upward/*concentric*) characterization and terminology.



Source: Adapted from "A Joint Power Approach to Define Countermovement Jump Phases Using Force Platforms," by J. R. Harry et al., 2020, *Medicine and science in sports and exercise*, *52*(4), 993–1000.

Unloading, unweighting and yielding

This phase which begins at the start of movement has been referred to both as the "unloading" as well as the "unweighting" phase, and both agree on the event that marks the beginning of this phase–vGRF falling below body weight (A). However, some authors and software refer to a single period which ends at the point at which the vGRF returns to bodyweight (point C), hence, "unweighting" (i.e., McMahon et al, 2018) while others distinguish between an unloading phase which ends at minimum force (point B), followed by a yielding phase (B-C) which begins at minimum force and ends at the point at which vGRF returns to bodyweight (Harry et al., 2020). These two approaches can be summarized as either:

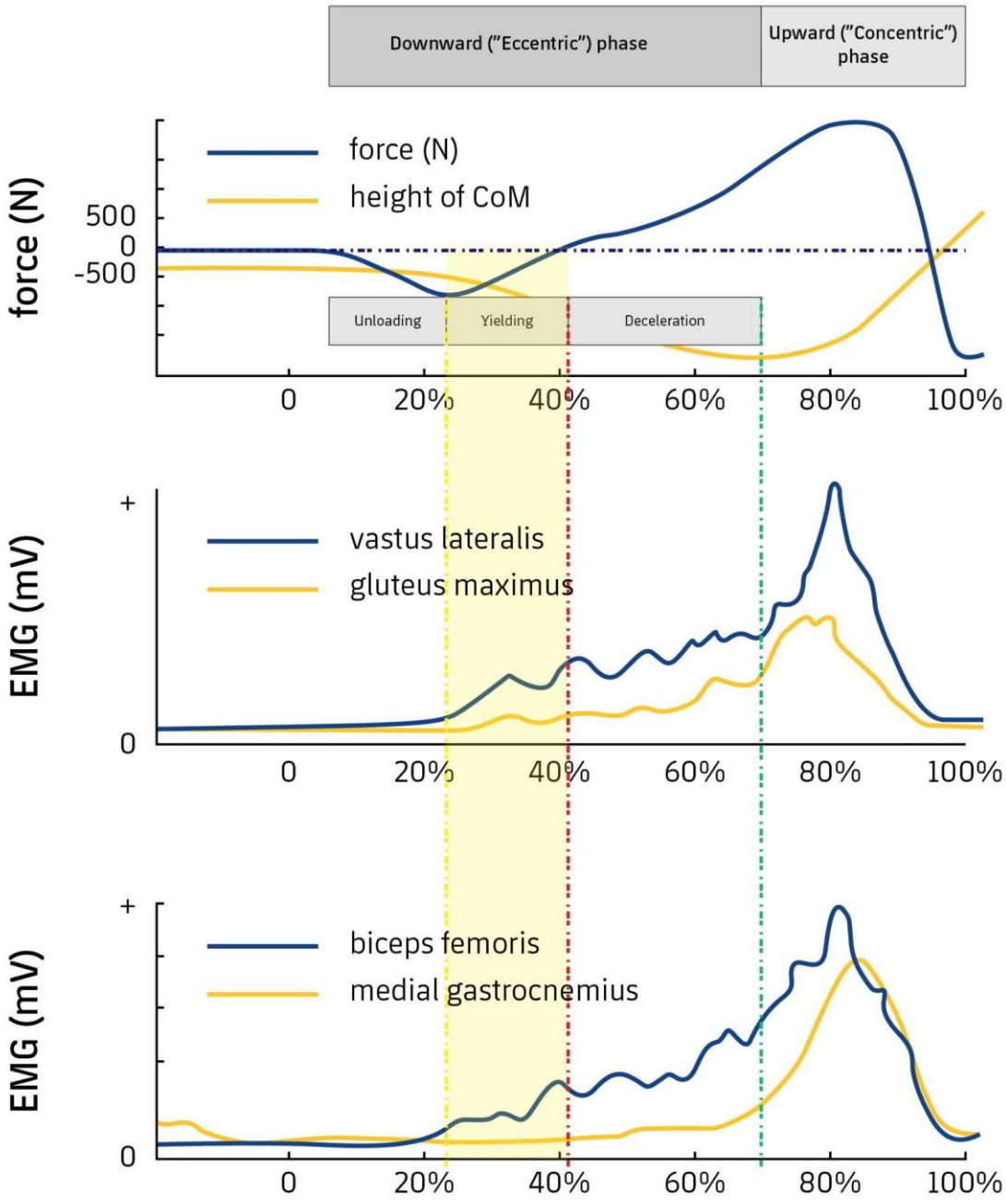
1. Unweighting-braking/deceleration (no yielding phase)
2. Unloading, yielding, braking/deceleration

Note that although the discrepancy between approaches 1 and 2 do not only relate to terminology but also reflect that in approach 1 the yielding phase is not considered a phase of interest. Whereas, considering yielding as a not completely passive phase is reflected in the use of the term "eccentric" to refer to yielding + deceleration (figure 3). The term yielding was proposed to refer to the COM yielding to gravity without being totally passive, distinguishing it from the unloading phase during which the agonist's muscles relax and the centre of mass displacement descent is essentially unresisted. A recent article also referred to this period as the "transition phase" (Warr et al., 2020). It is suggested that the yielding phase represents the time for muscle-tendon slack uptake and achieving an active state (Harry et al., 2020) a process which underpins the efficient transfer of force from the musculotendinous unit to the bone.

Yielding could be described as a "pre-deceleration phase" analogous to beginning to apply the brakes in a car accelerating down a hill, before an observable decrease in the car's speed which occurs during the deceleration phase —identified as the time point immediately after peak eccentric velocity. While the yielding phase is ignored by a number of researchers, calculations of lower body total joint power (hip + knee + ankle) during the CMJ based on a combination of force platform and motion capture data show that eccentric work is performed during this phase (Harry et al., 2020), beginning soon after minimum force (the start of the yielding phase). EMG activity is also reported in lower extremity muscles (Sahrom et al., 2020) during this phase which is evident in figure 4 - which shows the onset of increases in biceps femoris and vastus lateralis activity after minimum force. Therefore, during the yielding phase eccentric muscle activity evidenced by the EMG activity drives the positive rate of force development and increase in eccentric power (figure 3). In this respect, joint-level mechanics begins prior to the observable beginning of the deceleration of the COM–reflected in external mechanics (Harry et al., 2020). Note that there is also interest in the magnitude of force at the start of the yielding phase, which has been termed as "unload vGRF" or minimum

eccentric force and is suggested as an indicator of the production of kinetic and elastic strain energy (Harry et al., 2018).

Figure 4: Muscle activation (EMG) in selected lower limb muscle groups across phases and subphases of the CMJ.



Source: data from "The use of yank-time signal as an alternative to identify kinematic events and define phases in human countermovement jumping," by S. B. Sahrom et al., 2020, *Royal Society open science*, *7*(8), 1-21, with phases (as defined in figure 1) overlaid, highlighting muscle activity during the yielding phase.

Due to data from this phase often not being reported, there are few reports on whether it provides information relevant to the characterization of athlete status or changes thereof.

However, meaningful changes in this phase were observed after COVID-19 home confinement induced detraining in male professional footballers (Cohen et al., 2021) and assessments during rehabilitation and following return to sport after anterior cruciate ligament reconstruction in a case report in a female professional player (Taberner et al., 2020). The observation that these changes were of large magnitude and didn't align timewise with changes seen in the deceleration phase suggesting that the yielding phase may be sensitive to specific types of loading and unloading. The author therefore recommends phase analysis using approach 2 (unloading, yielding, braking/deceleration)

Table 2. Unweighting/Unloading/Yielding phase variables

Variable	Description
Unloading duration	Time from the start of the movement to the beginning of the yielding phase
Unweighting duration	Time from the start of the movement to the beginning of the deceleration phase
Yielding duration	Time from the "minimum force" moment to the beginning of the deceleration phase
Minimum (eccentric) force / Unload vGRF	Instantaneous local minimal force during the downward (eccentric) phase. Defines the start of the yielding phase.
Yielding RFD	Force change between the start of the yielding to the start of the deceleration phase, divided by the yielding duration.

Source: Prepared by the author

Eccentric deceleration/braking phase

This final downward/eccentric subphase, most commonly termed either the deceleration or the braking phase, begins at the time point at which vGRF returns to body weight and of peak negative velocity (eccentric peak velocity). Note that ForceDecks - Vald Performance uses the term eccentric deceleration, while other systems may use "braking". Some literature may simply describe this subphase as the "eccentric" or "stretching" phase. This phase has consistently been identified as a relevant phase to analyse and report on in profiling, monitoring and rehabilitation/return to sport.

During this phase, the COM is descending, predominantly due to knee flexion, but deceleration of that mass has begun and substantial increases in EMG activity in the lower extremity muscle groups are evident, particularly towards the end of this phase (figure 4 above) as maximum countermovement depth is reached and momentary zero velocity prior to the upward phase.

Table 3. Deceleration/braking & overall downward phase variables

Variable	Description
Deceleration/Braking subphase	
Eccentric Deceleration* phase duration	Time from the start of the deceleration phase (defined by peak eccentric velocity) to zero velocity and maximum negative displacement (countermovement depth).
Eccentric Deceleration* impulse	Net force (above body weight) accumulated over the deceleration phase.
Eccentric Deceleration* RFD	Change in force over the deceleration phase (force at 0 velocity - force at maximum negative velocity) divided by the duration of the phase
Force @ 0 velocity	Instantaneous force values at zero velocity / maximum negative displacement
Countermovement depth (Maximum negative displacement)	The maximum displacement of the centre of mass during the jump phase.
Eccentric* peak/mean velocity	The peak marks the start of the deceleration phase. Note that an inadequate and consistent EPV has an important impact on the validity and reliability of all other eccentric variables (except for impulse)
Cross-sub phase variables	
Eccentric peak / mean power	Eccentric power begins to accumulate in the yielding phase, with the peak occurring within the deceleration phase. Mean is average across the whole downward phase
Eccentric RFD	Force change between the start of yielding and the end of the deceleration phase (i.e., force at 0 velocity - minimum eccentric force), divided by the time between these two subphases
Eccentric Duration	Despite the varied definitions of what constitutes “eccentric” during the downward phase, the literature referring to this variable in load-response monitoring defined this as the time from the start of movement to zero velocity / maximum negative displacement

*or “braking”; RFD=rate of force development

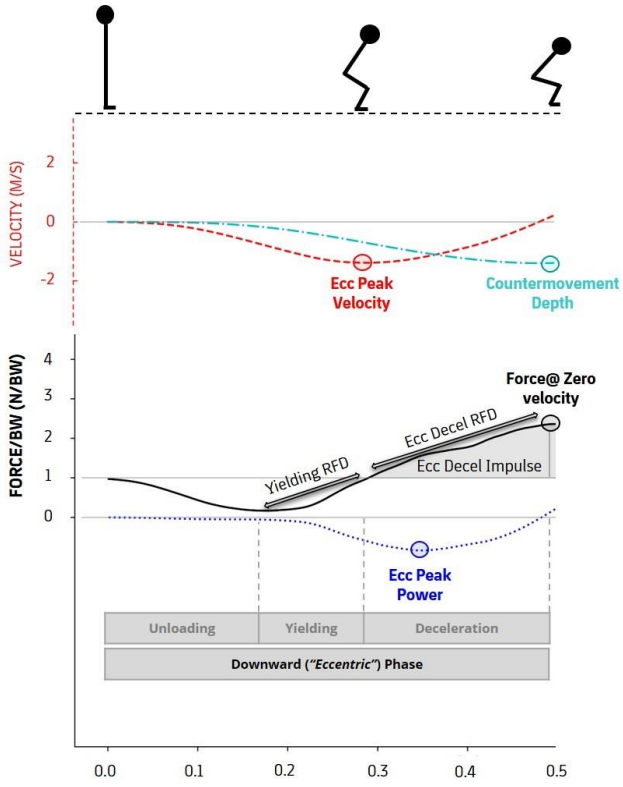
Source: Prepared by the author

Zero velocity /" amortization"

The moment at which COM velocity is zero and maximum countermovement depth (displacement) is reached is not a phase, but a time point that divides the downward/eccentric and upward/concentric phase. It has also been referred to as the (unload and "amortization vGRF") whose magnitude is suggested to represent the storage of kinetic and elastic strain energy (Barker et al., 2018; Bobbert et al., 1996). Bilateral (total) force at 0 velocities has been examined principally from the perspective of fatigue monitoring (Gathercole et al., 2015; Gathercole et al., Kennedy & Drake, 2017; Ruggiero et al., 2022) and asymmetries in this variable in the characterization of post-ACL deficits. However, higher values of force at 0 velocities (relative to body weight) were also associated with better jump performance in a sample of 100 mixed NCAA division athletes (McHugh et al., 2020) and in Rugby 7's athletes (Floria et al., 2016).

The "amortization phase" is a term that has been used in strength & conditioning to describe a pause or time delay between these two phases in plyometric exercises, which theoretically reflects SSC ability, meaning a shorter pause is a positive outcome of this form of training. However, when examining displacement and velocity traces within the CMJ in athletes, it is generally difficult to discern "a pause". Indeed, McMahon et al. (2018) suggested that an amortization phase may not be identifiable if the sampling frequency is inadequate or the athlete transitions very rapidly from the downward to the upward phase. To the authors' knowledge, the only proposal for a variable is that of Barker et al. (2018) who define this phase as the period of time when the COM was within a 1 cm threshold relative to the lowest COM– a potentially useful but arbitrary threshold that is independent of the overall displacement of the jump.

Figure 5: Visualisation of the downward phase and selected subphases and variables



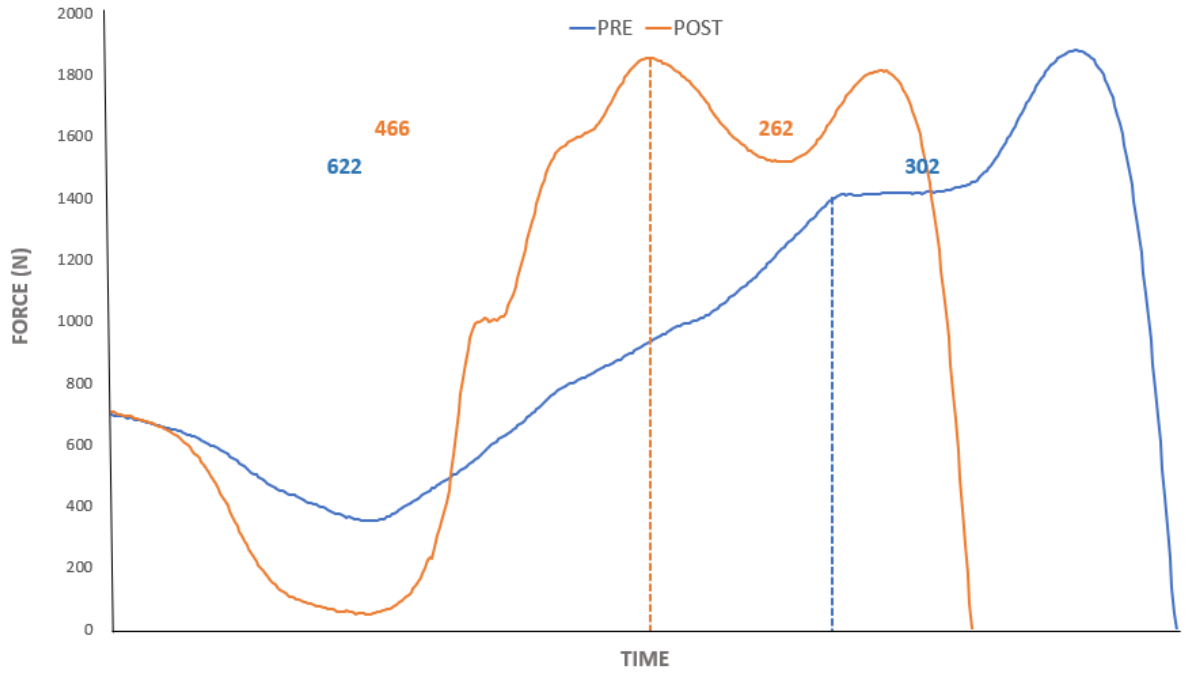
Adapted from Cohen & Kennedy, 2021

Upward ("concentric") phase

The upward phase begins after zero velocity (maximum countermovement depth /negative displacement) and ends at toe-off/take-off, is commonly known as the concentric phase, but also referred to in research and some force platform software as the propulsive or the push-off phase (Owen et al., 2014). From the velocity curve it can be defined to begin at the first time point of positive COM velocity (> 0.01 m·s-1) and cannot be accurately identified from the force-time trace alone, although in many athletes, a peak in force coincides with this end of the eccentric/beginning of the concentric phase (McHugh et al, 2020). Some of the most commonly reported performance variables such as peak power and force are derived from this phase, and it is the overall impulse generated during this phase and velocity achieved at take-off which is the strongest correlate of jump height (Winter, 2005). Even so, the downward more detailed examination of its kinetics during this phase and its subphases (and as discussed below, the waveform or shape of the force-time trace) may yield greater diagnostic insights in profiling and monitoring of healthy and rehabilitating athletes.

As in the eccentric deceleration phase where the net impulse is calculated, impulse over the phase represents the integration or sum force at all-time points is expressed in newton seconds (Ns) and therefore increases may not represent an increase in the force applied at any given time point or even an increase in mean force indeed, but both could show the athlete is producing a lower magnitude of force at given time points but accumulate the same impulse - by doing so over a longer period of time (due to a greater range of motion / COM displacement). Therefore, opposing changes in concentric duration and the magnitude of force could mask a positive (i.e., decreased duration and increased magnitude) or negative (i.e., increased duration and decreased magnitude) change in the peak magnitude or distribution of force applied–i.e., a stable concentric impulse can be observed despite substantial underlying changes in kinetics/strategy. This is illustrated below in figure 6 and table 4, which shows an example of a professional footballer assessed at two different time points (the start of preseason and 5 weeks later) in which he displays almost identical concentric impulse of 216-217 Ns. However, in the second assessment, the duration of the phase is substantially lower and a larger magnitude and proportion of that impulse is produced earlier in the phase; as reflected in concentric impulse-100 and in the ratio of Concentric-100 to total Concentric impulse.

Figure 6: Stable concentric impulse with alterations in shape and concentric impulse-100



Pre (blue) and post (orange) preseason CMJ best trial. Vertical dashed lines indicate end of downward (eccentric)/start of upward (concentric) phase. Selected data shown in table 4.

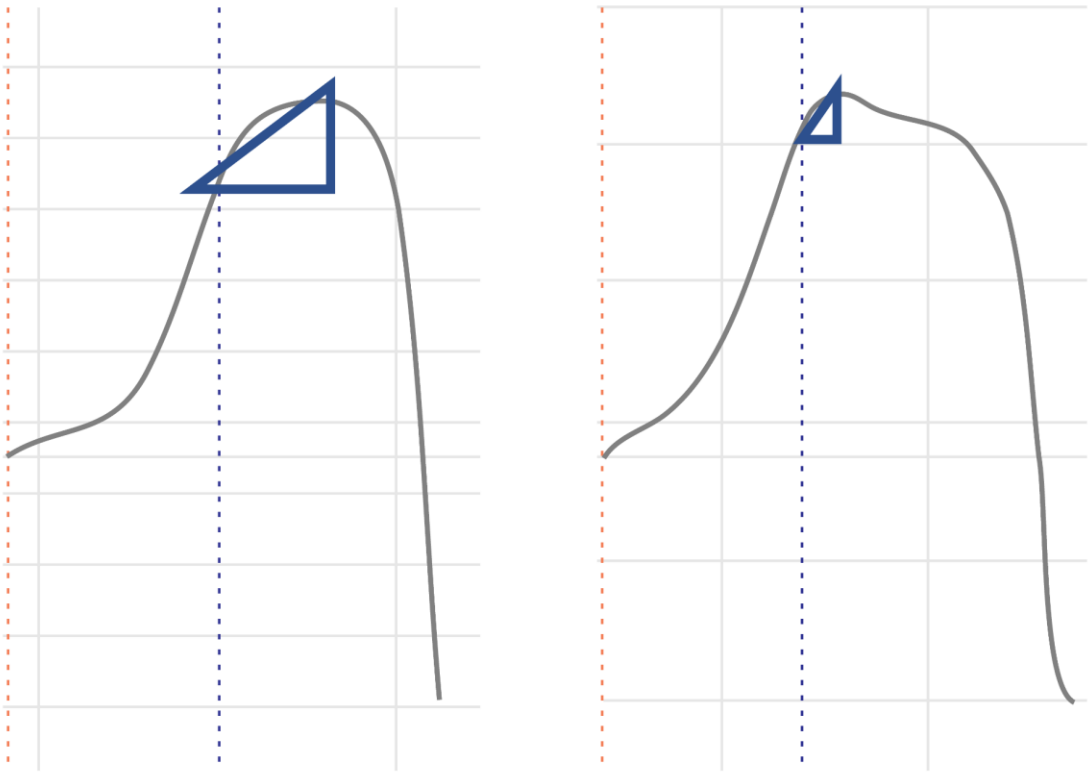
Source: Prepared by the author.

Table 4. Selected concentric kinetics at two-time points in a professional footballer

	Preseason (Panel A)	Start of the season (Panel B)
Concentric impulse (Ns)	215	216
Concentric impulse-100 ms (Ns)	63.6	93.7
Concentric impulse -100ms: total impulse ratio	0.30	0.43
Concentric duration (ms)	302	262
Concentric peak force (N)	1854	1844

These force-time traces also demonstrate the principal issue with the use of RFD in the concentric phase. The stronger association between rate of force development and sprint/acceleration performance than peak force in other neuromuscular performance / strength diagnostic tests, underlies the interest in also obtaining concentric RFD from the CMJ. The importance of considering the shape of the force-time curve during the upward phase has been highlighted by several researchers in this field. Theoretically, concentric rate of force development, (change in force over the change in time) would be used to describe the ability to rapidly increase force production in the phase. In isometric tests, rate of force development would typically be calculated over epochs such as 0-50 or 0-100 ms, 100-200 or 0-200, another approach is to take the average from the start of the phase to the peak. An alternative RFD is the maximal/peak–usually calculated as the highest RFD over a short window, such as a 5 ms epoch across any part of the phase. The traces below show examples of where a positive RFD can be determined across epochs.

Figure 7: Upward (*concentric*) phase force-time curves which allow positive RFD calculations

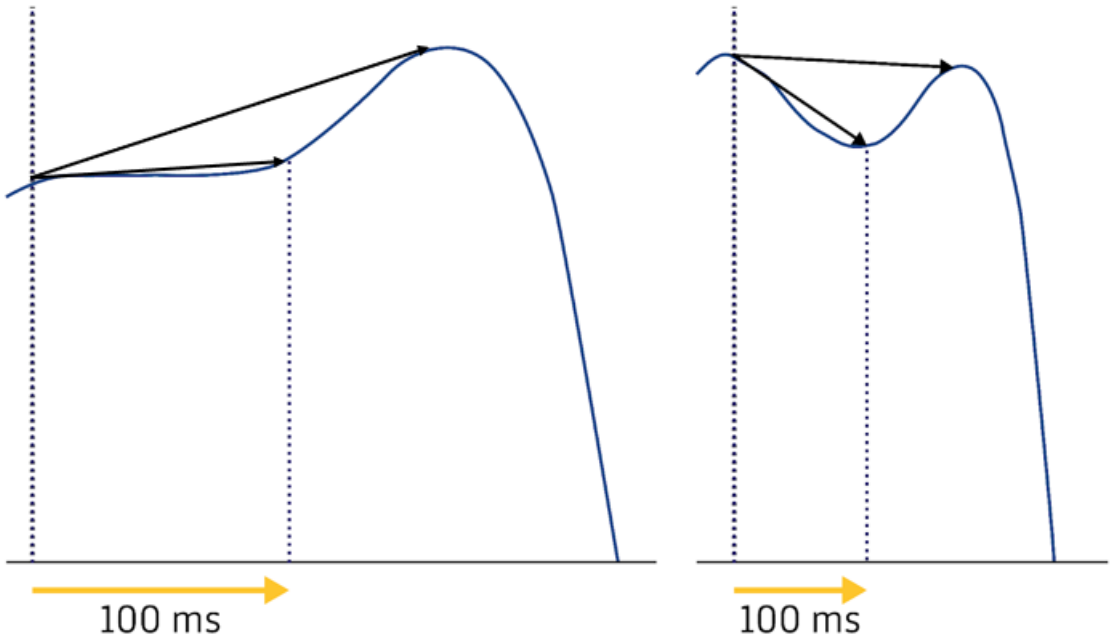


Source: Prepared by the author

Figure 7 shows two examples of CMJ trials in which positive concentric RFD can be calculated. However, following the start of the concentric phase a decrease in vertical force is often observed such that a negative RFD results. This and the substantial variations in the shape of the curve that are observed not only between athletes (Kennedy & Drake, 2018), but also within athletes over time (as shown in figure 6) or even across a series of trials (McMahon et al., 2018), makes it difficult to consistently determine concentric RFDs. Because of this, systematic use of the concentric RFD is therefore not recommended; although it could be used with athletes with consistently positive concentric waveforms - which necessitates decisions to be taken on an athlete-by-athlete basis and systematic inspection of FT curves.

Consider the two traces shown for the player shown above in figure 6, with the concentric phase isolated below for clarity:

Figure 8: Upward (*concentric*) force-time curves at two points - highlighting potential RFD calculations



Dark dashed line=start of upward/concentric phase. Light line=100 ms after the start of phase. The left panel shows the preseason profile during which two positive RFD epochs could be determined (0-100 ms and 0 to peak force) whereas post preseason, both were negative.

Source: Prepared by the author

Upward phase (*concentric*) force-time curves and RFD calculations in a player shown above in figure 6 and table 4–at two tests 5-6 weeks apart. Panel A: small magnitude positive RFD 0-100 ms, larger average RFD (0 to peak). Panel B: negative RFDs 0-100 and average (to peak) can be observed. seen in the player despite improvements in other measures/indicators of rapid force production (i.e., increased concentric impulse-100).

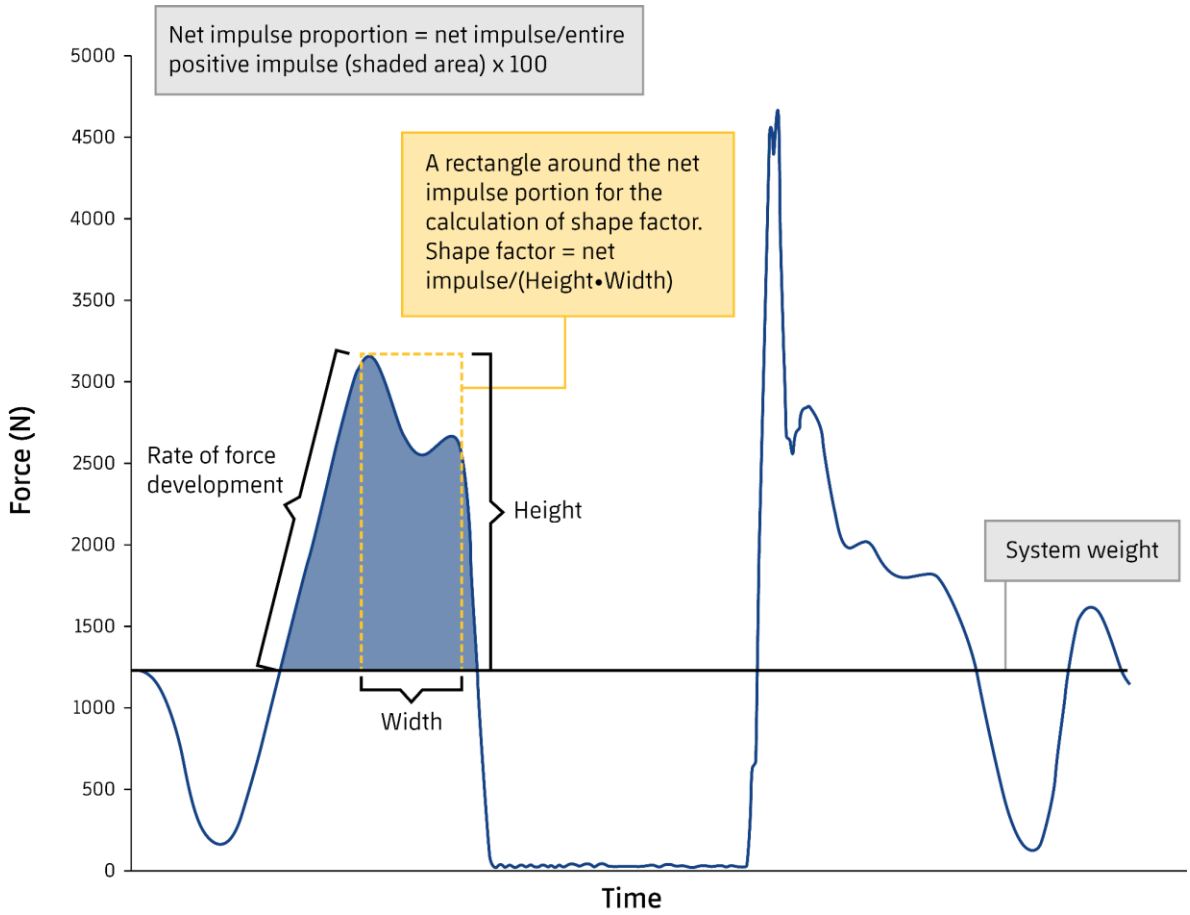
In the first test assessment, there is a slight positive RFD over 50 and 100 ms and a larger value to peak force, but it is clear that at assessment 2 both epochs based (0-50/100 etc) or the start of the peak are both negative slopes. Furthermore, such force-time profiles (with negative RFDs) are relatively common. Classification of force-time profiles or "waveforms" are discussed below. However, these classifications provide a descriptive analysis of the waveform type or "mode", not a numerical value. Therefore, other approaches are recommended to obtain a numerical value which characterizes the shape or distribution of force/impulses within this phase and the athlete's ability to produce a force rapidly / express "explosiveness" during the upward (concentric) phase. These measures not only show better reliability than concentric RFD (Merrigan et al., 2020), but more importantly, they have also demonstrated good sensitivity by discriminating between athletic ability (Cormie et al., 2009), short-term residual (Taberner et al., 2020), and chronic (Kijowksi et al., 2015) response to loading or injury related unloading:

- Time-constrained concentric impulse over the first 0-50 or 0-100 ms of the upward (*concentric*) phase.
- Concentric rate of power development variables, representing the slope of the power-time trace during the phase (Cormie et al., 2009) average (start of phase to peak power) or over specific epochs, such as 0-50 or 0-100 ms).

These and other variables within the upward (*concentric*) phase are shown below in figure 9.

Although not aimed at specifically characterizing the early concentric phase, “shape factor” (Dowling & Vamos, 1993) and net impulse proportion are analyses designed to quantify positive impulse (above body weight) shape. In practice, however, in most cases, the input for both of these variables will be concentric phase impulse (figure 9). To calculate shape or net impulse, height (magnitude of force) and width (duration of force application) of impulse are first determined, and the total impulse above bodyweight that would be achieved if that peak height was maintained across the full length of time (drawing a rectangle around this area), is calculated. Both variables (formulas shown in figure) denote the ratio of the actual impulse produced during this period relative to the maximum impulse that could be achieved (represented by the rectangle).

Figure 9: Shape factor and net impulse proportion



Source: "A new approach to determining net impulse and identification of its characteristics in countermovement jumping: reliability and validity." By S. Mizuguchi et al., 2015, *Sports Biomechanics*, 14(2), 258–272.

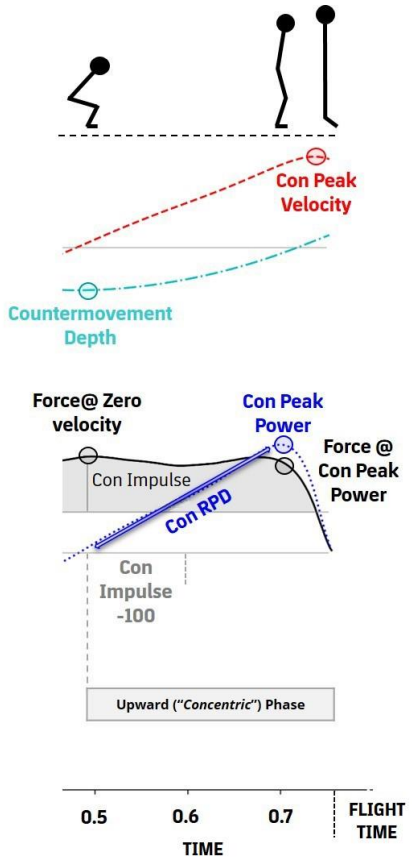
When attempting to quantify explosiveness in the upward (concentric) phase of the CMJ, it is important to remember that in contrast to the squat jump, the concentric phase of the CMJ is influenced by and reflective of performance during the eccentric phase and SSC function. This is the case cross-sectionally, but interventions targeting eccentric strength or power improve concentric performance and jump height (Cormie et al., 2009). In particular, the early part of the concentric phase is influenced by the late eccentric phase (Sole et al., 2018). We also noted a strong correlation between eccentric deceleration RFD and concentric impulse-100 in a large sample of elite footballers: r=0.956 ($p<0.001$), whereas the association with overall concentric impulse was much weaker (r=0.13, p=0.046).

The neuromuscular function is not only reflected in peak or mean forces (or impulse) but also rate of force production, time-constrained impulse metrics and phase durations–reflecting the ability to produce or initiate force production more rapidly and reach higher magnitudes or attain a peak within a shorter period of time. There is some evidence from isometric assessments such as the mid-thigh pull, indicating that RFD characteristics may be more strongly associated than peak force with some aspects of sprint performance (Wang et al., 2016; Townsend et al., 2019).

With respect to associations between performance in the CMJ or other jump and other aspects of dynamic performance, the few studies that have examined associations between CMJ kinetics broadly, or more specifically, compared CMJ peak versus RFD metric correlations with sprint, change of direction or agility, do not suggest that CMJ derived RFD is more strongly associated with these motor performances than peak values. In professional Australian rules footballers, Morris et al. (2020) reported significant correlations between relative concentric peak force (N/kg) and split times during a 40m sprint–5m, 10m and 20m, while correlations were not significant for 30 or 40 m times. Markstrom & Olsson (2013) evaluated a number of CMJ kinetic variables in elite sprinters (N=5), including force and RFD/force and impulse and modelled components of sprint performance. They found that only jump height and con peak force (only body mass relative variables were significant in a regression): peak force /kg and max velocity over 10m and 60m and jump height in maximum velocity over 10m.

Below are the upward/concentric phase variables commonly referenced and others of interest in monitoring the healthy and/or rehabilitating athlete, but less frequently referred to in the literature, but also are visualized (figure 10) and summarized (table 5).

Figure 10: Upward phase (*concentric*) variables



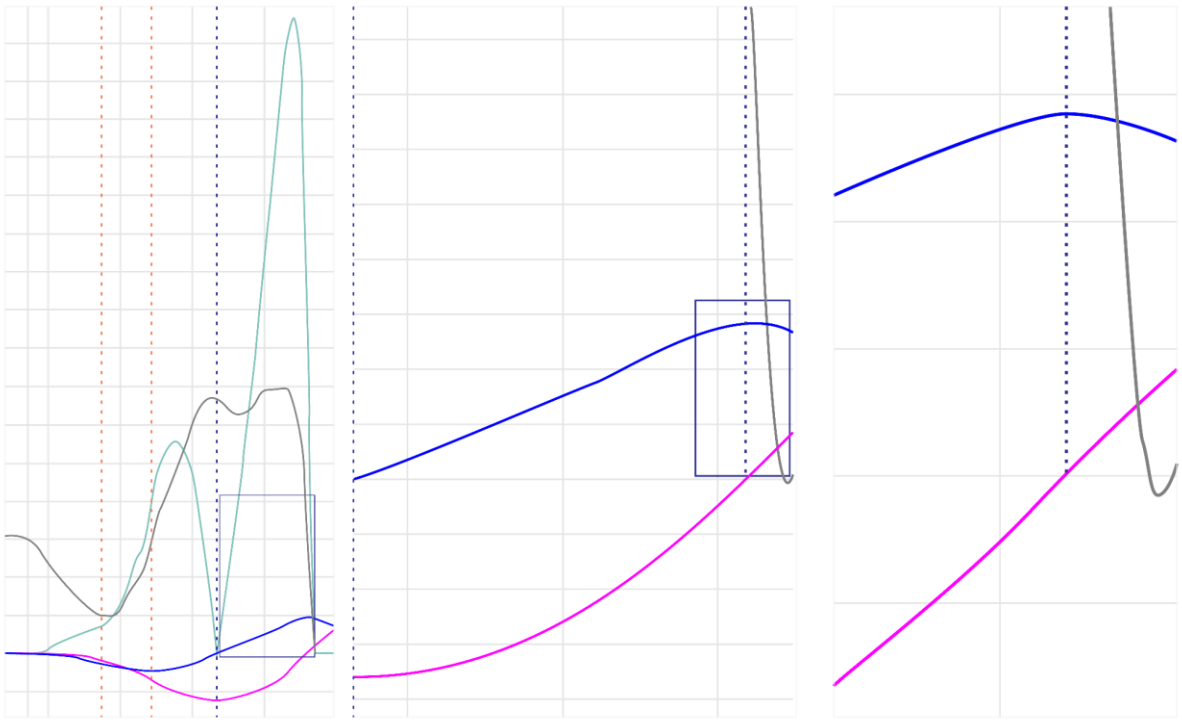
Variable	Description
Concentric Impulse	Net impulse (above bodyweight) across the whole phase
Concentric Impulse-50/100 ms	Net Impulse during the first 50/100 ms of the phase
Concentric main force *	The difference with impulse is that it only reflects the average magnitude of force at all time points across the concentric phase and not the accumulation. Therefore, it is not directly affected by time over force.
P1 P2 Concentric impulse	Net impulse during the first 50% and second 50% timewise of the concentric phase.
Concentric peak force	Instantaneous local maxima during the upward phase. Timepoint at which it occurs vaies accros and within athletes (trial-wise and longitudinality) deppending on waveofrm shapes.
Force Concentric peak power	Instantaneous force at the timepoint of peak power and therefore it is more anchored time and displacement-wise than peak force.
Peak Power	Instantaneous local maxima on power-time trace.
Mean Plantar flexion power	Mean power of the timepoint at which zero displacement is reached until take-off. Note that the validity of this variable relies on the quality of the displacement trace.
Rate of power development RPD - 50/100 ms	Stope of power trace form start of concentric phase to peak power or... From start to 50ms or 100ms after start of phase
Peak Velocity	Peak occurs around the timepoint at wich centre of mass displacement returns to zero. At which point velocity declines until take-off
Velocity at peak power	Deppending on the shape of the waveform, the velocity at peak power may also be peak velocity.
Take of velocity	Velocity at the last timepoint prior to take-off used to estimate jump using the impulse momentum equation.

Source: adapted from Cohen & Kennedy, 2021

The upward/concentric phase of the jump is a triple extension activity (of hip, knee, and ankle joints) involving a temporal proximal to distal (hip-ankle) lower limb joint dominance in terms of contribution to the overall vGRF. Note, however, that vGRF is also influenced by foot musculature. This sequential joint dominance is also reflected in the muscle activation patterns across these joints (figure 12). While the specific patterns vary between athletes, the displacement-time trace allows an ankle dominant/plantar flexion subphase to be defined– from the point at which the displacement curve becomes positive (figure 11), in other words, a higher centre of mass than at the start of movement when the athlete was weighed (flat-footed/neutral ankle position). Here, the additional height or positive displacement at take-off represents an additional centre of mass displacement due to plantar flexion, and has been referred to as contact height (Riggs & Sheppard, 2009). It is suggested that the loss of velocity during this phase may be a limiting factor in jump height – ultimately determined by take-off velocity. It is important to note that the validity of this variable is highly dependent on the accuracy of body weight measurement and stability, since it is derived from the displacement curve and therefore highly vulnerable to error related to these factors. Jakobsen et al. (2012) defined the variables "plantar power" and a ratio of concentric peak velocity to the take-off reflecting the loss of velocity during this phase which begins when the centre of mass

displacement and force is equal to that of the start of movement/standing centre of mass velocity declines from its peak as the weight of the shank and foot segments add to the effective mass that is being accelerated (Peterson et al., 2017), as such this phase has been described as the propulsion-deceleration phase, in contrast to propulsion-acceleration before this point.

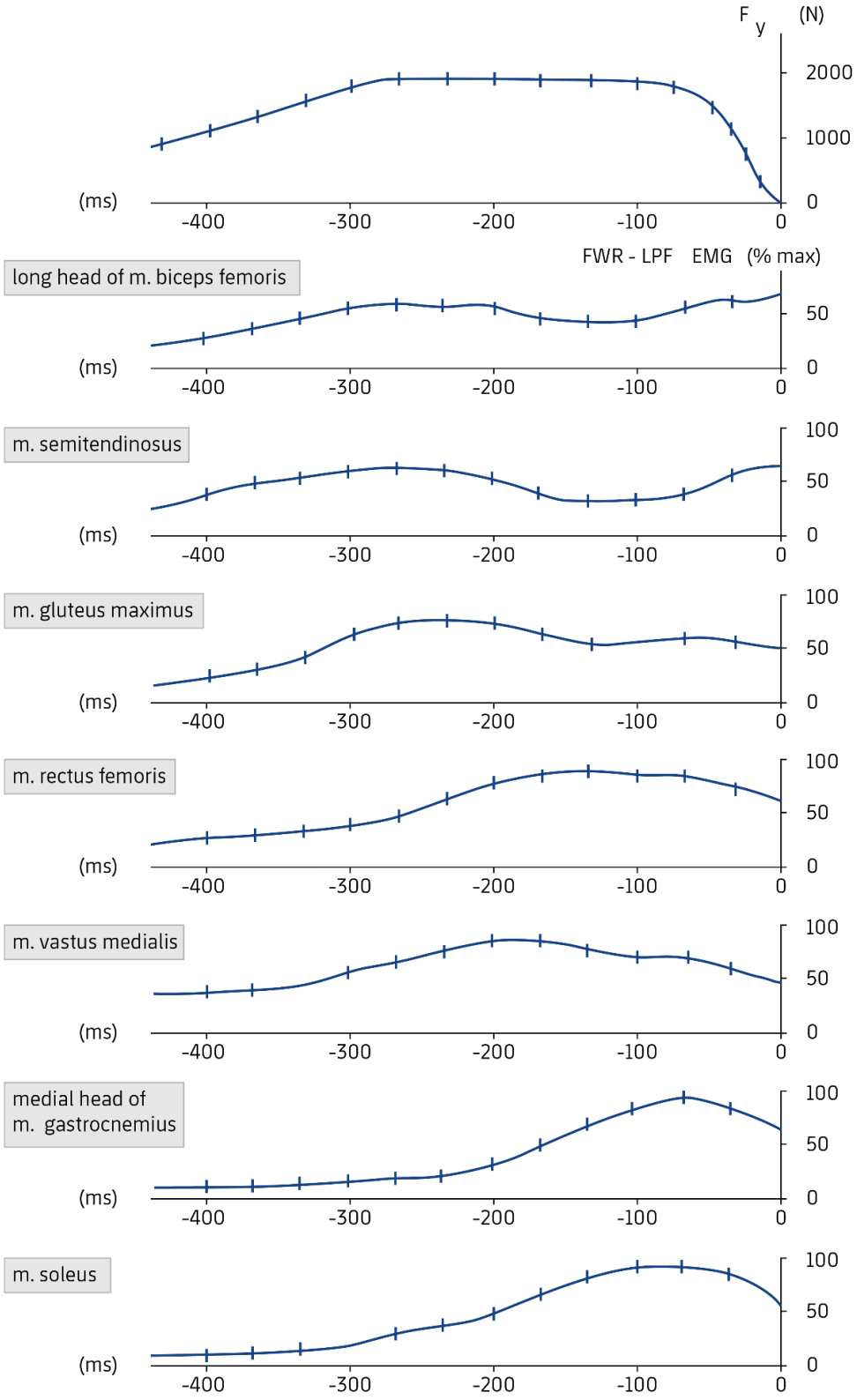
Figure 11: "The plantar flexion phase"



Source: Prepared by the author.

The dominance of the ankle joint and plantar flexion during this subphase suggests a substantial influence on the magnitude of the decline in velocity between peak and take-off relative to the knee and hip joints and musculature and is of interest to the practitioner. Note, however, that EMG studies indicate that peak gastrocnemius activity occurs before peak power, while peak knee extensor occurs before this–as a proximal to the distal pattern of activation characterizes the take-off phase as evident as shown in figure 12. However, additional characterization of the relative contributions and timings of the musculature involved in the CMJ may be possible via waveform or mode classification, in that these waveforms have been correlated with specific activation patterns, as discussed below.

Figure 12: Lower limb EMG activation during the countermovement jump



Source: from "Coordination in vertical jumping," by M. F. Bobbert & G. J. Schenau, 1988, *Journal of Biomechanics, 21*(3), 249–262.

Flight phase

Determining the start and end of this phase and therefore the flight time–one of the methods used to estimate jump height, is conceptually simple; it begins at take-off or toe-off and ends on the first contact on landing. In practice, however, thresholds for defining those two points must be defined manually, in your Excel/Matlab script or by the force platform software providers, and as highlighted regarding the start of movement, different methods can influence the determined value for flight time. This is in addition to the aforementioned joint position issues that impact on the estimation of jump height from flight time once it is determined.

Jump height is principally estimated using the flight-time method or the impulse-momentum method. Neither measure centre of mass displacement directly, and therefore both are subject to error when their calculations are based on assumptions being violated in some way. Nonetheless, the impulse-momentum approach is generally considered to be "superior" to the flight-time method, principally due to the potential for differences in joint position on take-off and landing which can undermine this method's accuracy by undermining its fundamental assumption: that the maximum displacement of the COM during flight occurs at the midpoint (timewise) of the flight phase. This depends on a further assumption that COM displacement at take-off (which exceeds zero because of plantar flexion) and landing are equal. Therefore, if during flight the athlete flexes ankles, knees, or hips during flight or takes off on toes and lands flat-footed, it will undermine this assumption; the distance between centre of mass and point of contact at take-off and landing will change. The athlete should extend fully during flight, but younger athletes or inexperienced jumpers may flex knees, hips or ankles during flight/landing–a practice which should be corrected by coaching. This in turn undermines the flight-time assumptions. Due to this susceptibility to error, it has been suggested that the (impulse-momentum estimation) which calculates jump height from take-off velocity is preferable (Hara et al., 2008). This method, which is not susceptible to the aforementioned joint position issues, has the potential to be more accurate. In practice, however, the disadvantage of the imp-mom method is its potential to be affected by other aspects of assessment–mainly bodyweight measurement and pre-jump instability which can accumulate error in velocity and therefore accurate determination of take-off velocity, from which jump height is estimated using this method.

Landing

The start of the landing phase is conceptually obvious, like the take-off, unless you manually define it in a spreadsheet or graph, this event will be detected using a threshold value, typically 10 or 20 N. The reason for not using a lower number is to reduce the risk of a false landing being detected due to vibrations within the surrounding. Currently, the kinetic analysis of the landing phase (landing duration) encompasses the period of time from landing impact/ground contact to zero velocity as in countermovement depth in the jump phase, and as in the jump phase, the latter is also the time point at which the lowest centre of mass displacement is reached during landing, in other words, corresponding to the deepest squat position/knee flexion during landing. The landing phase has also been subdivided into a "loading" phase, which begins at ground contact and ends at peak landing force, and an "attenuation" phase from peak landing force to the end of the landing phase (Harry et al.) (figure 14). These phases have also been referred to as the "impact" and "stabilizing" phase, respectively.

Generally, either flat-footed or forefoot to rear foot landings are observed after a bilateral vertical jump with Ballet or other sports with aesthetic constraints being exceptions. It is suggested that the forefoot/rear foot is more common when the athlete is conscious of landing and is associated with a lower peak force than the flat-footed variant (Bressel & Cronin, 2005). In both cases, most landings result in two force-time peaks–the first of which is associated with the impact of the metatarsal heads (F1), and the second with impact of the calcaneus (F2) (figure 15). These typically occur 10-15 and 30-70 ms after first contact (Ortega et al. 2008) with timing influenced by factors such as foot length and muscle activation patterns.

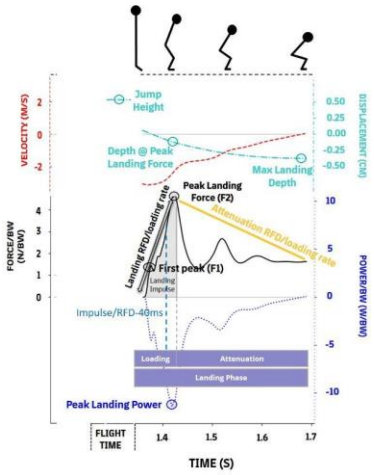
The magnitude of the peak force and shape of the force-time trace during the landing phase is affected by joint biomechanics, muscle activation and technique (Aerts et al., 2013) (the specifics of which are discussed below in profiling). It is important to be aware that the body of research related to landings is far larger regarding drop jump (first landing particularly) and drop landings than for CMJ landings and that while there are some similarities between landings across all of these assessments, findings from research or measurement of one are not entirely applicable to interpretation of the others. For example, the drop jump first landing creates a distinct demand from a CMJ landing, even if both were from the same height. In the drop jump, the athlete aims to decelerate as rapidly as possible on the first landing to create positive acceleration to minimize the time as much as possible on the ground and to immediately perform a maximal jump. On landing from a conventional CMJ (or SJ, DJ 2nd landing), the athlete also must absorb the impact forces and reduce downward velocity to zero–albeit without having the necessity to do so rapidly. The overall net impulse required to decelerate from the velocity at impact to zero velocity equals the impulse generated in the upward/concentric phase of the jump–as this net impulse depends on the athlete's bodyweight and their centre of mass velocity, which is determined by the height the athlete

has landed from (their jump height). Landing velocity is therefore determined by the height of the jump (at any given body mass) a higher jump (and therefore higher take-off velocity) means a greater velocity on landing and requires a larger net impulse to attenuate this force to decelerate and completely brake downward movement (reach zero velocity). Note, however, that across a group of athletes while F1 correlates with jump height, peak landing force (which in the vast majority of cases occurs at F2) does not. This might seem paradoxical based on the physical principles described, and it is important to note that, while jump height is not a significant determinant of F2 (peak landing force) across a group of athletes, within an individual (assuming technique has not changed) greater jump height is associated with significantly higher F2. In elite footballers, we observed a significant 15% increase in peak landing force in a group of players who performed three submaximal jumps of (mean height: 33.2 cm) followed by three maximal jumps (mean height: 38.2 cm), although the range of change was a 44% decrease to a 13% increase. This highlights that while the overall force absorbed over time (impulse) is determined by jump height and body mass, interindividual differences in landing technique/biomechanics (muscle activation pattern, flexibility, and musculoskeletal stiffness (Baus et al., 2020)) exert an important influence on the magnitude of this peak. Indeed, peak landing force and the shape of the FT traces on landing can be acutely altered by instructions on landing technique (Milner et al., 2012), and chronically by neuromuscular training interventions. The author's preference is not to cue landing in CMJ assessments unless the specific purpose of the assessment is to coach and provide feedback on landing technique and landing forces. The reasoning for this is that by not cueing and not focussing on the landing but on achieving jump height, the jump is more aligned with what the athlete's typical on pitch/court strategy and is more likely to reveal their normal strategy under these conditions (Bates et al., 2013).

Considering the magnitude of load; 6.6 multiples of bodyweight (SD 2.1), that is absorbed during a period of approximately 350 ms (SD: 140), one can envision how different landing strategies could affect ligament and other soft tissue loading and influence risk of microtrauma in repetitive loading or traumatic mechanical overload and acute injury risk. On this basis, the landing phase of the jumps has principally been of interest from a strength and power diagnostic perspective related to injury risk and recovery from injury–with impact or landing forces stressing lower extremity soft tissues and thereby being a potential factor in injury risk, particularly in sports with frequent repetitive and high force landings (Bressel & Cronin, 2005). Bilateral landing and asymmetries in rehabilitation and RTS are discussed in the "A framework and toolbox for kinetics and kinematics in rehabilitation and Return to Sport" module of "Performance, Injury, and Rehabilitation Assessment Toolbox" course.

Landing phase variables

Figure 13: Key variables and subphases of the landing



Variable	Description
1st Peak impact force (F1)	Peak landing forces are typically reported relative to bodyweight (/kg or multiples of bodyweight–useful in comparing athletes across a group. Also, when monitoring an individual it can also be useful to report relative to jump height, if changes in jump height are expected (during rehabilitation), to account for the direct relationship between jump height and peak landing force within individuals
Peak force (F2) (peak landing force)	
Loading RFD ("loading rate")	Peak landing force (F2) or force at peak landing power divided by time from impact to the time point of peak force or peak power (average slope between points ignoring F1)
Attenuation RFD	Peak landing force (F2) minus force at maximum displacement/zero velocity divided time from peak force to this point (average slope–as there oscillations in force between these two points)
Landing / loading impulse	Impulse from impact to end of landing phase (landing impulse) or to peak force (loading impulse)
"Early" impulse or RFD	Impulse or RFD during the first 40-70 ms
Duration	The time from impact to the maximum displacement/zero velocity
Time to peak landing force / landing peak power	The time components of the landing RFDs (to peak landing/peak power) equivalent to the loading phase duration
Displacement at peak landing or peak power	Estimated COM displacement at the timepoint at either peak–representing early displacement/at end of loading phase
Maximum displacement (at zero velocity)	Estimated COM at end of landing phase (zero velocity)

Source: Adapted from Cohen & Kennedy 2021.

Note that until relatively recently, force platform CMJ landing kinetic analysis consisted principally of peak landing (F2) and average rate of force development (or "loading rate") were the only variables reported within the landing phase, with little description of subcomponents of phases. However, as during take-off phase where depth of the countermovement can be estimated from the displacement curve, one can also estimate the depth of centre of mass displacement at points such as peak landing force and the maximum displacement on landing with alterations reported following detraining (Cohen et al., 2020). These provide a proxy indicator of knee flexion on landing, of interest from an ACL injury risk/recovery perspective. Furthermore, as an ACL rupture on landing is estimated to occur 40-70 ms following impact, rate of force development and impulse from impact over these epochs have begun to be examined related to injury risk and rehabilitation. Note that practitioners should also be aware of a pre-landing/preparatory phase, which represents pre-activation strategies (as quantified with EMG and motion capture) adopted before impact (Lida et al., 2011). By definition, during flight GRF cannot be measured but differences between athletes (Baus et al., 2020) or changes in loading phase kinetics (vGRF and estimated COM displacement in particular) following acute of chronic interventions may be driven by differences or alterations, respectively in pre-landing lower limb and boot muscle activation (Lida et al., 2011) and joint kinematics (Horita et al., 2002).

Providing instructions on landing to absorb force and create a "soft" landing through increased hip and knee flexion (Milner et al., 2012) is effective in spreading the force absorption demand over a longer duration–creating a lower magnitude but longer duration and flatter impulse with a lower peak force (F2). This more flexed landing is contrasted with a stiff –high peak and shorter duration landing. Feedback on landing forces and asymmetries and the effectiveness of alterations in strategy on these values could be provided

immediately, and this approach using kinematic feedback has been shown to be effective in corrective training interventions (Ford et al., 2015). However, the author's preference is that as part of screening cues on landing should not be given to first understand the athlete's habitual landing strategy when not focused on landing technique but on the take-off and achieving maximal jump height, which is more representative of the on-pitch situation.

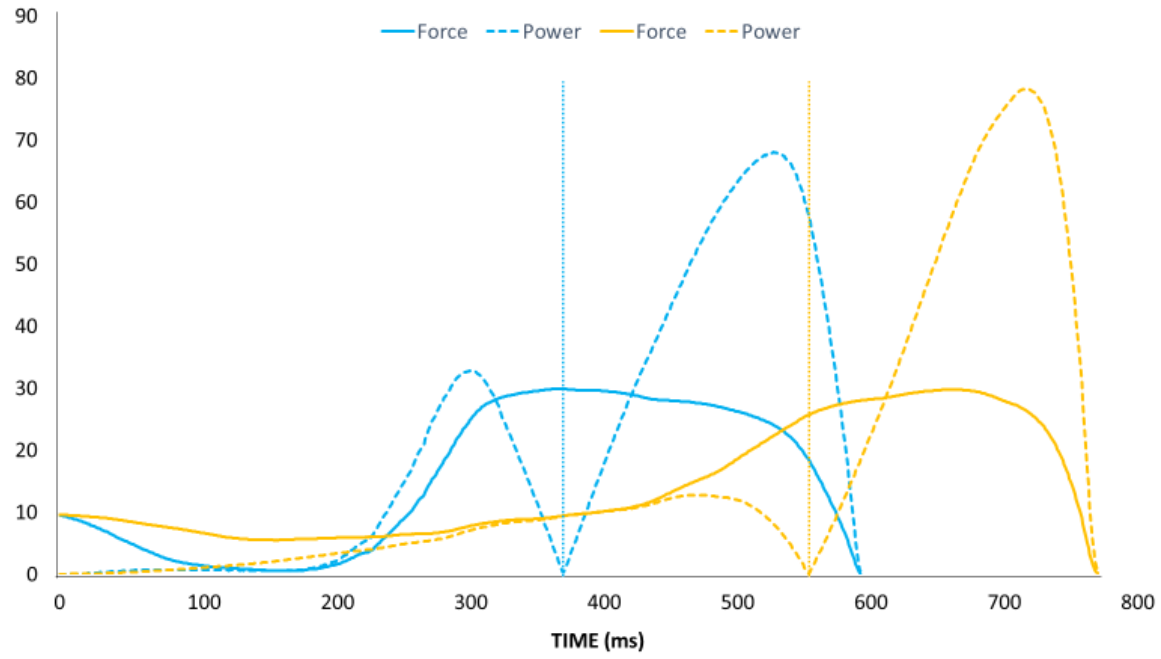
Waveform analysis

It might surprise the reader that after considering the large number of variables calculated in the force, velocity, power, and displacement curves in the CMJ across and within phases and subphases, that researchers have expressed concern that large amounts of kinetic data within the force-time curve are being discarded (Richter et al., 2014). One way to retain all of the force-time data within the analysis is by performing "waveform" or "temporal phase" analysis, a comparison of the complete trace across athlete groups at one time point or over time and identifying areas of difference or change rather instead of, or in addition to the analysis of variables derived from the kinetic traces. It is well recognized that sport background, strength levels and training influence the shape of the force-time, power-time and displacement time curves and not only values for discrete variables (Cormie et al., 2009; Cormie et al., 2010). However, more recent work has aimed to classify these different shapes or waveforms (Richter et al., 2014) and to understand their potential influence on performance (Kennedy & Drake, 2018) and associations to muscle activation and joint kinematics and response to fatigue. As highlighted earlier in this module, concentric waveforms shapes are somewhat characterized and quantified by rate and time-constrained variables already described (i.e., time constrained or shape of impulse in the concentric phase). Nonetheless, as highlighted above–there are specific aspects of the concentric force-time curve which make blanket approaches unsuitable or unable to fully characterize this phase. And as such further description/qualitative analysis has a role to play and the *potential* to add to the diagnostic understanding of athlete status at a given time point, and their response to loading, beyond that provided by variable outputs. In this module, we have focused our attention on the profiling of athlete status at a single time point (cross-sectional analysis) using variables derived from the kinetic traces during the phases of the jump. In this section, we examine how waveforms/profiles can contribute to that type of characterization.

Waveform analysis is principally used in research to compare groups at a single point or over time to try to determine differences or a change using statistical methods; it can also be used to visualize trends in an individual athlete, although currently is not widely used in applied settings. In contrast, waveform classification may provide some additional qualitative information which is associated with underlying activation patterns, albeit based on research in other populations/individuals–and should therefore be considered in that context. Note also that published research related to waveforms predominantly involves the analysis and visualization of time-normalized traces rather than raw force-time curves–whereby absolute

jump time for each trial is converted to a percentage with zero being the start of movement, and 100% the take-off. This step facilitates the statistical comparison of "ensembled" jumps with different durations. Time normalized curves are generally used in research where data collected from many subjects is displayed. This approach is useful in visualizing and identifying areas of interest and determining statistical inter-limb differences in force output. It is also used to compare total bilateral/combined vertical force in groups of athletes over time. While normalization allows comparisons of jumps with very different durations, by definition it removes duration from the analysis and visualization. Given the discriminatory capacity of durations in comparisons at a single time point and over time, it is vital that this information is also taken into consideration in analysis, using variables or visualizations. Visualizations of overlaid non time-normalised traces can be informative, as shown above in figure 6 to highlight the difference between total concentric impulse and concentric impulse-100. Figure 14 below provides an example of a non-normalized visual comparison of the data from the jumps described in table 1 performed by an elite footballer and weightlifter above, at a single time point.

Figure 14: Non-time normalized force and power, traces of two elite athletes with the same jump height.

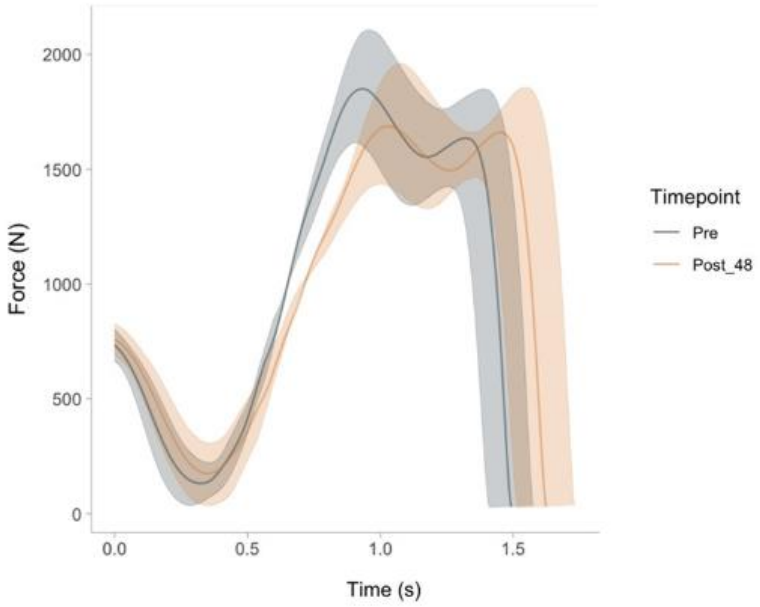


Footballer (blue) and Olympic weightlifter (orange) body weight relative (/kg) force (solid profiles) and power (dashed profiles) -time profiles. End of downward (eccentric) /start of upward (concentric) phase indicated by vertical blue dashed (footballer) and orange (weightlifter), respectively. Note that positive values are shown for downward phase ("eccentric") power, for the purpose of visualisation and contrast; note the very large differences in eccentric versus concentric power outputs in the two athletes (i.e., the weightlifter shows a higher concentric peak power but substantially lower eccentric peak power than the footballer). Note also the differences in phase durations. The numerical values for the two tests are given above in table 1a and b)

Source: prepared by the author

An alternative approach to visualise multiple athletes' data, retaining force and time (duration) data is splining. Figure 16 below shows CMJ mean and standard deviation data in 8 footballers at two time points (pre and post a fatiguing protocol). Equally this visualisation could be used to compare two groups of athletes. It could also be used to compare a single athlete over time.

Figure 15: Visualisation of CMJ waveform with retained force and time characteristics in footballers pre and post fatiguing protocol

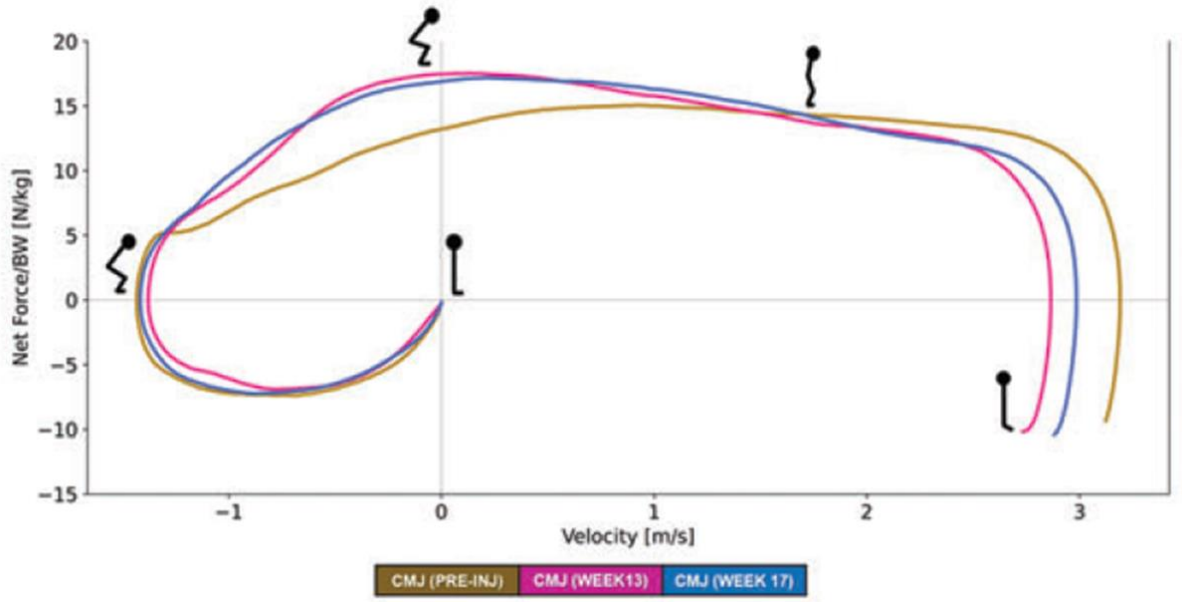


Visualizations were generated using a spline function (R). Raw jump trial data interpolated to 2000 data points, permitting the calculation of mean (the two lines) and the standard deviation (SD) below (mean -1 SD) and above (mean +1 SD) the mean - represented by the shaded area around the line.

Adapted from: Cohen, D.D, Spineti, J., Neto, A.P.F., Vianna, G., De Souza, D.F., Gathercole, R., Harper, D.J., Taberner, M. (2022). The effects of repeated sprints with and without rapid horizontal decelerations on residual neuromuscular fatigue in professional male footballers. Sports (abstract). 10,93: 8

Another form of visually and statistically examining changes or differences in CMJ performance (to compare an individual over time, compare group data at one time point or a group over time) is the creation of separate force-velocity, power-time, velocity-time or displacement time plots (Cormie et al., 2009). Visually, force-velocity "loops" (so called due to their shape), can be particularly useful in group or individual analysis, with an example shown below in an individual athlete (figure 16).

Figure 16: Force-velocity loop in elite footballer pre, during and post-rehabilitation.



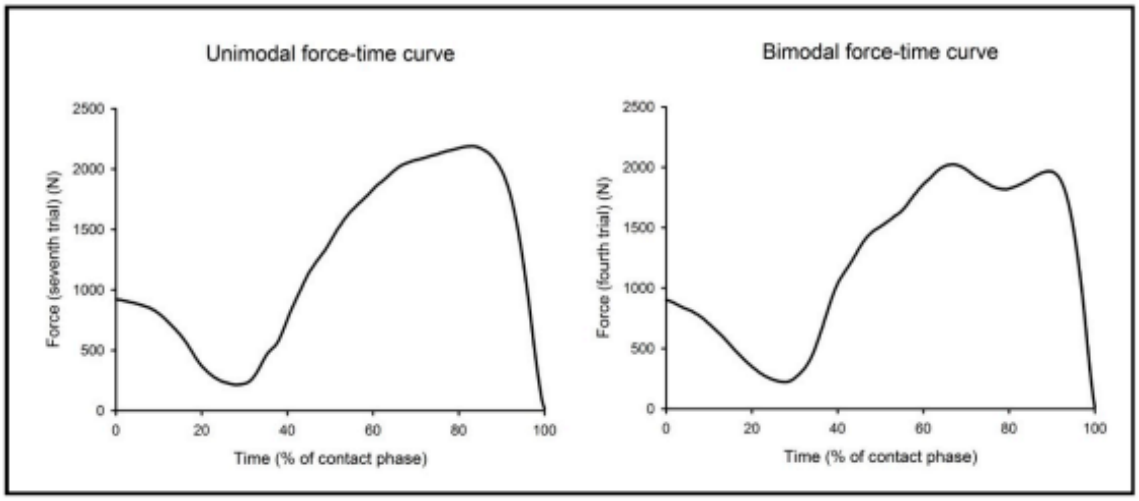
Stick figures help understand the position of the athlete, starting with the standing zero velocity position, followed by the downward phase (negative velocity values), reaching zero velocity gain at the end of the downward phase, followed by the positive velocity values during the upward phase.

Source: Taberner, M., Haddad, F.S., Dunn, A., Newall, A., Parker, L., Betancur, E., Cohen, D.D. (2020) b. Managing the return to sport of the elite footballer following semimembranosus reconstruction. BMJ Open Sport Exerc Med. Oct 26;6(1): e000898. doi: 10.1136/bmjsem-2020-000898.

Waveform classification

As highlighted above, waveform classification can be useful to provide additional insight on a specific athlete at one time point and examine acute/residual and chronic changes. It has also been that before performing waveform analysis, waveform classification should first be performed, and analysis performed separately on groups who belong to each waveform cluster. Richter et al. (2014) suggested that the variation in waveforms within a group of athletes means that a single group analysis could mask performance-related factors that are affected by the "shape" of the force-time curve. Across the research in this theme, up to 4 waveforms have been described. The most basic classification that can be easily visually defined is a unimodal (a single peak) and a bimodal (two peak) form (figure 17).

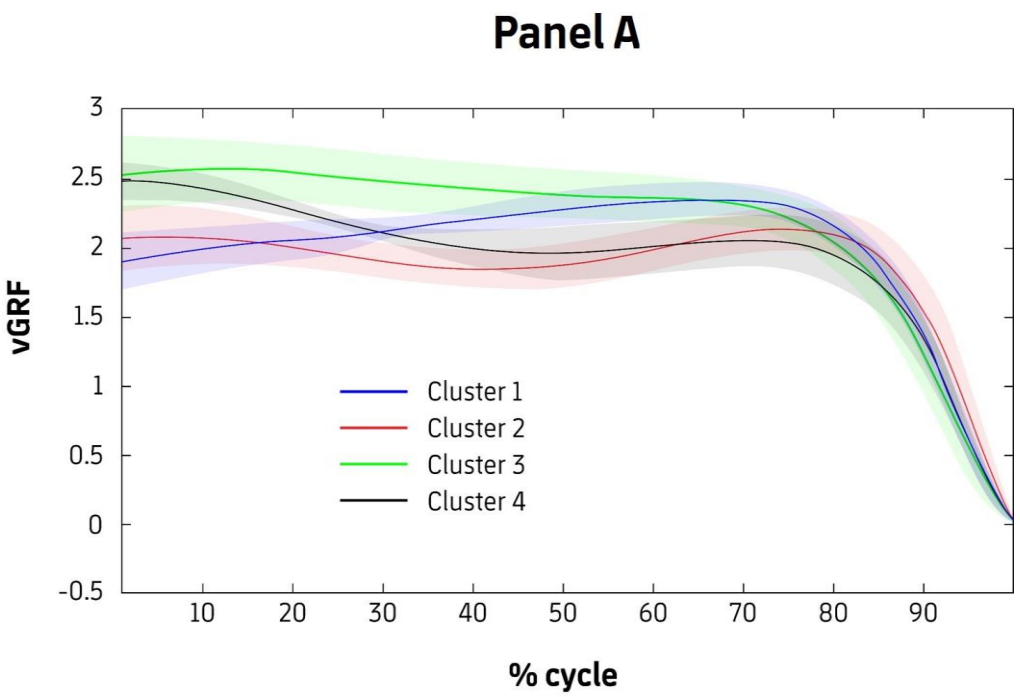
Figure 17: unimodal vs bimodal waveform. A comparison of the same athlete.



Source: Lake, J. P., & McMahon, J. J. (2018) p.4

However, using statistical processes of principal component analysis performed on the time normalized curves, followed by k-mean clustering analysis of substantial sample sizes has identified four or three waveform modes or clusters with analysis of full waveforms of the full waveform (from start of movement to take-off) or of the net impulse waveform (beginning at the eccentric deceleration phase and ending at take-off), respectively (figure 18 panel A and B, respectively).

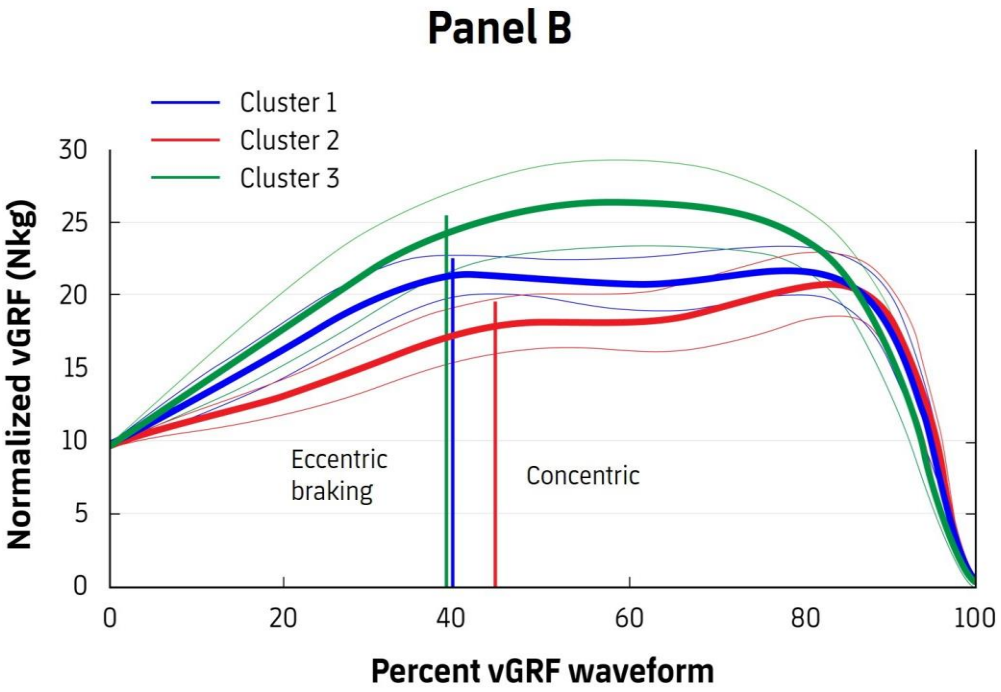
Figure 18 A: Waveform clusters



Note: Means of curves clusters generated using k-means clustering with four clusters

Source: from "Clustering vertical ground reaction force curves produced during countermovement jumps," by C. Richter et al., 2014, *Journal of biomechanics*, *47*(10), 2385–2390.

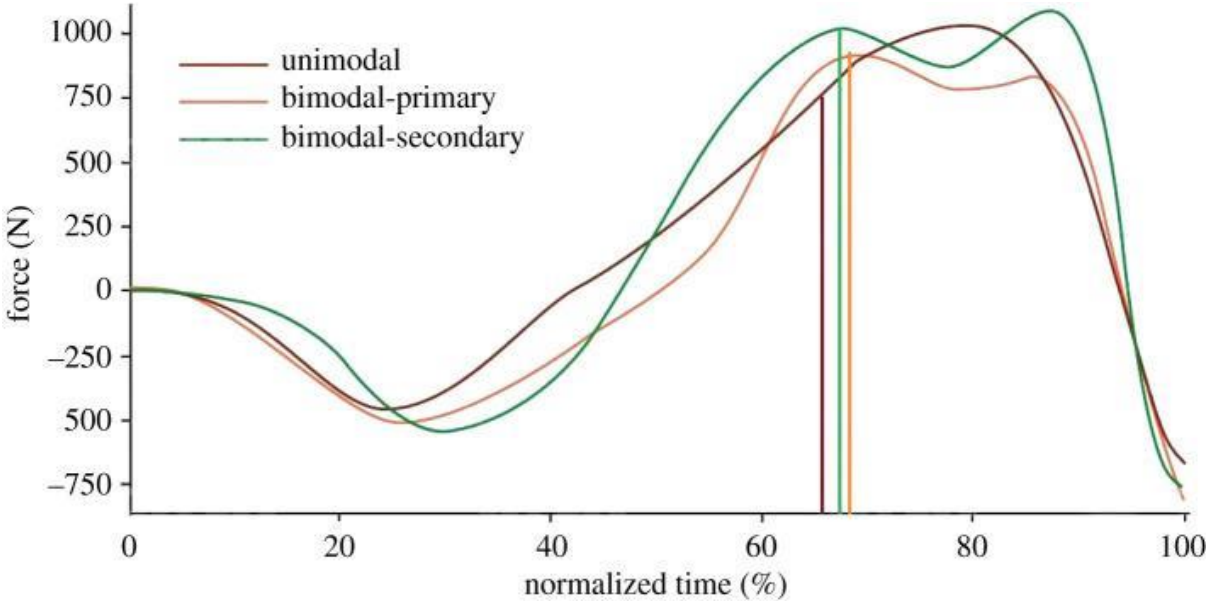
Figure 18 B: Waveform clusters in college athletes



Note: Average vGRF waveforms (eccentric deceleration (braking) phases) for each cluster. The average transition point, from eccentric to the concentric phases, is also shown for each cluster as a vertical line.

Source: from “Force-Time Waveform Shape Reveals Countermovement Jump Strategies of Collegiate Athletes,” by T. M. Guess et al., 2020, *Sports 8*(12), 1-13.

Figure 19: Uni and bimodal-primary and secondary waveforms



Source: Sahrom et al. (2021) p.19

Panel A: clusters of 122 male athletes from various sports (Richter et al., 2014). Cluster 1 and 2 unimodal of these are unimodal (1 peak) and two bimodal (two separate force peaks). Subcategories of uni and bi, defined according to the timing and magnitude of the peaks across the jump cycle. Panel B: 394 male and female US collegiate athletes across various sports (Guess et al., 2020). Three waveform clusters (1 unimodal and 2 bimodal) using eccentric braking (deceleration) + concentric phases.

Richter et al. (2014) found no significant differences in jump height between the clusters, suggesting that these clusters represent “strategies” or sequencing of force and application and joint kinematics not consistently associated with greater jump height, but reflect different means of achieving it. In contrast, Guess et al. (2020) found significant differences in jump height and kinetics across three clusters they identified using eccentric braking (deceleration) + concentric phases: significantly higher values in cluster 3 athletes for all kinetic variables analysed. Similar jump heights in cluster 3 and 2 but significant differences in terms of the time constrained values versus overall force outputs - cluster 3 having a higher deceleration RFD but lower impulse in the eccentric deceleration phase and shorter durations in the eccentric deceleration phase and across all other phases. Cluster 1 had lower jump height and longer phase durations. Therefore, these waveform clusters appear to approximately cluster or “bucket” three performance-kinetic profiles or relatable categories within any athlete sample; good jump heights and short jump time, good jump heights with moderate jump times, and poor jump heights and slow jumps. An approach that parallels a quadrant (median split) analysis if short jump time and poor jump height was added. While the analysis by Guess et al. (2020) appears to support the concept that waveforms are associated with better or

more efficient performance, the heterogeneity of sports and mixture of male and female athletes makes it somewhat difficult to determine whether on an individual athlete basis these waveform classifications would provide distinct information from that of the kinetic variables – as differences for all kinetic variables were significantly between clusters.

Furthermore, in a study of over 100 high-level athletes across a number of sports McHugh et al. (2020), who examined both waveform mode and whether the peak force occurred at zero velocity/maximum displacement or not, concluded that while unimodal jumps, and bimodal jumps that are classified as (in which the initial peak exceeded the second peak) showed better jump height and kinetics, the occurrence of peak force at zero velocity was more strongly associated than the shape of the waveform. Sahrom, who examined only concentric phase waveforms, also reported significantly shorter concentric duration in unimodal than bimodal jumpers, with the longest durations in bimodal-primary. They did not report correlations with jump height or kinetic variables.

Table 7. A summary of waveform classifications

	Unimodal		Bimodal	
Richter et al., 2014 Mixed sports males (Gaelic football, hurling and basketball) Bimodal: 61/122	Cluster 1 Peak occurs shortly after the start of the concentric phase	Cluster 2 Low initial vGRF, peak occurs at about 70% of the jump	Cluster 3 High initial vGRF, peak occurs shortly after the start of the concentric phase,	Cluster 4 Initial vGRFs similar to both the first and second maxima where peak could occur either before 15% or around 80% of the movement cycle
Guess et al., 2020 Mixed sport university males and females (swimming and diving, wrestling, cheer, cross-country, softball track and field Volleyball, basketball, golf, soccer, tennis) Bimodal: 336/394	Cluster 3 A single hump peaking approximately at 1/3 of the way through the time in the concentric cycle.		Cluster 2 Two peaks of similar magnitude, the 1st at start and the 2nd at the end of the concentric phase.	Cluster 1 Plateau at the start of the concentric phase, peak at the end of the concentric phase
Sahrom et al 2021 Physically active males Bimodal: 20/32	Unimodal-Primary* < 10% difference in (normalized) timepoint between max displacement and peak force	Unimodal-Secondary > 10% difference in (normalized) timepoint between max displacement and peak force	Bimodal-Primary* Two peaks with 1st ≥ 2nd	Bimodal-Secondary Two peaks where 1st < 2nd by 10%

Source: Prepared by the author based on “Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping”, by Richter, (2014). “Force-Time Waveform Shape Reveals Countermovement Jump Strategies of Collegiate Athletes,” by T. M. Guess et al., (2020); “The use of yank-time signal as an alternative to identify kinematic events and define phases in human countermovement jumping”, by Sahrom, S.B., (2021).

Note: Bimodal-primary is the default bimodal profile unless it meets the criteria for bimodal-secondary.

The work of Sahrom et al., highlighted in several places earlier in this module, provides data which if confirmed in other groups does suggest information gain from waveform classification, relevant to individual athlete status and, potentially, adaptations to performance or injury risk interventions in the healthy athlete or status and progress in rehabilitation. They aimed to determine whether waveform clusters/modes were associated

with a specific movement pattern or muscle activation strategy. They found that the unimodal waveform was associated with highly aligned knee flexion, ankle plantar flexion and peak EMG activities (figure 5, left). Whereas, they suggested that a second peak that characterizes the bimodal shape might be explained by a timewise separation of knee and ankle extensions and peak EMG activities after maximum displacement.

It is important to be aware that waveforms have been reported to show within-subject inconsistency in athletes signal (Lake & McMahon, 2018) with Lake and McMahon reporting that over 3 trials 13% of a sample of 18 Rugby players consistently produced unimodal waveform, but none were consistent over 5 trials. The bimodal force–time curve shape was consistently demonstrated by 67% over 3 and 5 trials. Instructions or cueing, known to affect several kinetic variables, has been shown to impact the appearance of uni versus bi modal curves. Pérez-Castilla et al. (2019) found that cueing to perform a deeper countermovement led to an increase in bimodal force-time curves (100%) while cues for a shallower countermovement led to a larger number of unimodal outputs (65-88%).

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