Understanding the Key Phases of the Countermovement Jump Force-Time Curve

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UNDERSTANDING THE KEY PHASES OF THE COUNTERMOVEMENT JUMP FORCE-TIME CURVE

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Abstract

The countermovement jump (CMJ) test is commonly conducted to assess neuromuscular function and is being increasingly performed using force platforms. Comprehensive insight into athletes' neuromuscular function can be gained through detailed analyses of force-time curves throughout specific phases of the CMJ, beyond jump height alone. Confusingly, however, many different terms and methods have been used to describe the different phases of the CMJ. This article describes how six key phases of the CMJ (weighing, unweighting, braking, propulsion, flight, and landing) can be derived from force-time records to facilitate researchers' and practitioners' understanding and application to their own practice.

Introduction

Force platforms are among the most frequently used biomechanical apparatus in the field of Sports Biomechanics and strength and conditioning (S&C) research, but S&C practitioners have historically sought cheaper field-based alternatives to test their athletes' physical status. Affordable and valid commercial force platforms have been recently developed (17, 27), meaning that S&C practitioners are more likely to utilize them in the future. A common test included in athlete testing batteries and the associated scientific literature that is performed on a force platform is the countermovement jump (CMJ). The CMJ is appealing because it is quick to perform, non-fatiguing and requires minimal familiarization, yet it can yield valuable insight into an athlete's neuromuscular and stretch-shortening cycle (SSC) capabilities (3, 4, 9, 21, 22).

Recent studies have shown that a comprehensive insight into athletes' neuromuscular function can be gained through detailed analyses of force-time curves throughout specific phases (7, 16, 28, 29, 32) or the entire CMJ (3, 4, 9, 21, 22), when compared to measuring the output of the jump alone (i.e. jump height [JH]). Therefore, it is important that practitioners who wish to use force platform-based assessments of CMJ can recognize the constituent parts of the CMJ force-time curve, and understand their relative contribution to CMJ performance and how they can be manipulated through coaching and training. To achieve this, the different CMJ phases must be identified using robust methodologies; this has not always been the case in the research literature and so warrants discussion with a view to its practical application (28, 29). This may be because the identification of some CMJ phases requires the derivation of other variables from force-time data, or due to the many different terms used across studies to describe the different CMJ phases (5, 12, 14, 21, 22, 24, 25, 32-34).

As the use of force platform-based CMJ assessment across research and applied settings appears likely to increase because of the increased availability of affordable force platform systems, and because, as mentioned above, many different terms have been used to describe the different CMJ phases in the literature (some of which are less obvious than others), clarification of the key CMJ phases, along with simpler descriptions of them, seems timely. The purpose of this article, therefore, is to outline the key CMJ phases using simple, but

accurate, terminology to facilitate the collection, understanding, and practical application of CMJ force-time data by S&C researchers and practitioners.

Initial Assumptions

Before describing the CMJ phases, it is important that the reader is aware of the initial assumptions related to the examples discussed in this article, given that they can significantly influence the resultant force-time records. Firstly, the data presented in the figures contained within this article are taken from a single athlete's CMJ trial (apart from data shown in Figure 4 which includes two CMJ trials [of the three performed in total] from the same athlete). The CMJ trials included in these Figures were collected as part of a recently published study from the lead author's laboratory (19), thus institutional ethics approval and written informed consent was provided before testing. A summary of the data collection and analyses procedures used to acquire the CMJ trials presented in this article is presented in Table 1. Please note that the vertical and horizontal axes have been re-scaled across Figures 1, 3, 5 and 6 to align the force-, velocity- and displacement-time records for ease of phase identification.

INSERT TABLE 1 ABOUT HERE

It is beyond the scope of the present article to discuss the limitations of force platform-only analyses. If the reader is interested in further understanding the benefits and limitations of force platform-only analyses, then we refer them to an excellent article by Linthorne (15). Additionally, if the reader requires further information about different force platform technologies (e.g. those which include strain gauges versus piezoelectric sensors) then we refer them to an excellent applied article by Beckham et al. (2). An important point to note is that researchers and practitioners should attempt to establish sources of error associated with whichever force platform they use, in line with previous investigations (33, 34). It might be that some force platforms demonstrate a poor ability to register rapid changes in force (1), for example, and so the data may need to be treated, in the form of digital filtering, before being analyzed. If of interest to the reader, a detailed discussion of various smoothing techniques, as they apply to dynamic force-time records, can be read in the previously mentioned applied article (2).

Weighing Phase

The first CMJ phase is the weighing phase (sometimes referred to as the silent period (21, 22) or stance phase (34)), whereby the athlete is required to stand as still as possible (Figure 1), usually for at least 1 second (21, 22, 25, 26). The purpose of the weighing phase is self-explanatory, it is to weigh the athlete, but its importance is possibly less obvious, and it is therefore likely to be a phase which is overlooked by researchers and practitioners. Accurate calculation of bodyweight (BW) is essential for two reasons: firstly, it is used to identify a threshold to determine the onset of movement (to be discussed in the following section) and secondly, it (or, rather, the body mass derived from it) is included in forward dynamics

procedures (Figure 2). BW is usually calculated as the average (mean) force reading over the weighing phase (21, 22, 26), although some studies have subtracted the peak residual force during the flight phase (when the force platform is unloaded) from the average force during the weighing phase to account for signal noise (14, 34). It is likely that the latter approach is more accurate as the noise in the force signal will vary from trial to trial, but while flight phase noise will provide information about the signal noise per se, it cannot inform the researcher/practitioner about 'human noise' during the weighing phase. The most important consideration here is that a consistent approach to BW determination is applied to enable fairer data comparisons between trials, sessions and athletes.

INSERT FIGURE 1 ABOUT HERE

INSERT FIGURE 2 ABOUT HERE

The reason for the suggested weighing duration of 1 second is largely a consequence of a study conducted by Street et al. (33) which showed that weighing durations of $\geq$ 1 second leads to a $\leq$ 1% overestimation of JH (calculated based on the impulse-momentum relationship) when compared to the maximum weighing duration of 2 seconds (34). A $\leq$ 1% overestimation of JH is considered acceptable (26, 33), thus we recommend that the weighing phase should last for $\geq$ 1 second. It is essential, however, that the athlete remains stood upright and as still as possible during the weighing phase as it is vital that center of mass (COM) velocity and displacement equal zero at the onset of movement for the numerical integration method to be accurate (34). Street et al. (33) showed that, when subjects were stood still, integrating the force-time data using the trapezoid rule (i.e. commencing forward dynamics procedures) anywhere from 0-1.5 seconds (the time range tested) before the onset of movement had no meaningful effect on JH. It would seem fine, therefore, for force-time data integration to commence from the start of the weighing phase. It is important to note, however, that a 0.5% error in body mass (BW · gravitational acceleration^{-1}) during the weighing phase can induce errors in JH, although this error is diminished when integrating force-time data over a sufficient duration and frequency (34). From a practical perspective, to ensure that at least a 1 second weighing phase is achieved, starting data collection on the word "2" during a "3, 2, 1, jump" command works well based on the authors' research and experience.

Unweighting Phase

The second CMJ phase is the unweighting phase, whereby the athlete commences a countermovement by first relaxing the agonist muscles (18), resulting in combined flexion of the hips and knees, including some dorsiflexion. The unweighting phase begins at the onset of movement which is usually identified as the instant at which BW is reduced below a set threshold value of force. The threshold value of force used to identify the onset of movement has varied across studies (6), but the most recent "criterion" method was suggested by Owen et al. (26). This method identifies the onset of movement as the instant when vertical force is reduced by a threshold equal to 5 times the standard deviation of BW (calculated in the

weighing phase), hence the importance of standing still during the weighing phase (i.e. to minimize the standard deviation of BW and thus increase the sensitivity of the onset of movement threshold). Owen et al. (26) recommended going back 30 milliseconds from the onset of movement because they identified that movement would have already started by this instant and thus COM velocity would not equal zero. A 5-10 millisecond error in identifying the onset of movement has little effect ($\leq 0.1\%$) on the derived COM velocity and displacement calculations, however, due to a lesser rate of change in force at this stage when compared to take-off and landing (see later sections) (14). Although misidentifying the onset movement may have little effect on forward dynamics procedures, it would likely have a more profound effect on time-related variables (e.g. time to take-off, time to peak force etc.) and thus associated metrics such as rate of force development (6) and reactive strength index modified. It would be prudent, therefore, to at least adopt a consistent threshold across trials, sessions and athletes for comparative purposes.

INSERT FIGURE 3 ABOUT HERE

The unweighting phase continues from the onset of movement through to the instant at which force returns to BW (12, 14, 18, 21, 22, 24, 32), on the ascending aspect of the force-time curve (Figure 3a-b). Therefore, the unweighting phase, as the name implies, comprises the entire area of the force-time curve (before take-off) that is below BW (Figure 3a-b). The instant at which force returns to BW coincides with the instant at which peak negative COM velocity is achieved (Figure 3a). Plotting the velocity-time curve alongside the force-time curve is visually useful, therefore, in revealing the exact point at which the unweighting phase ends (Figure 3a). For a given athlete (whose body mass is constant during a CMJ trial), a greater unweighting net impulse will lead to a greater peak negative COM velocity (as impulse [force × time] = Δ momentum [mass × Δvelocity]) which will then require an equally large net impulse to be applied in the subsequent braking phase to reduce momentum to zero (14, 24). The unweighting phase is important, therefore, as it influences the rate and magnitude of force production required in the braking phase which, in turn, will likely influence SSC function (14).

Braking Phase

As mentioned above, the third CMJ phase is the braking phase, whereby the athlete decelerates (i.e. "brakes") their COM. Hence this phase commences from the instant of peak negative COM velocity (see above) through to when COM velocity increases to zero. This coincides with the bottom of the countermovement (i.e. the peak negative COM displacement/deepest part of the squat) (12, 14, 21, 22), as shown in Figure 3b. The braking phase has been called the "stretching phase" (14, 24, 32) and "eccentric phase" (20-22) in some previous studies, whereby it is assumed that the leg extensor muscle-tendon units are actively stretching to decelerate body mass but one cannot assume that all active muscles are stretching (i.e. medial gastrocnemius may actually shorten (15) during this phase). Also, one should remember that the analysis of vertical force-time data, and additional variables that are derived

via the integration of said data, provides insight into linear COM kinetics and kinematics only and does not inform us of joint or muscle-tendon unit behavior.

As mentioned earlier, the net impulse applied in the braking phase is equivalent to the net impulse in the unweighting phase (14, 24) because the net impulse required to stop a given mass travelling at a given velocity (in this case, the peak negative COM velocity) is proportional to the net impulse that was applied to reach said velocity from the start (i.e. when the athlete is standing still during the weighing phase). As a given net impulse can be achieved by applying a large force over a short time or a small force over a long time and variations in between, the shape of the net impulse produced in the braking phases will depend on the strategy employed by the athlete (20-22, 24, 32). If the athlete attempts to minimize braking phase time, as may be the focus if they are instructed to perform the CMJ as fast as possible, they will have to produce a large braking force to match the unweighting phase net impulse and reduce momentum to zero (Figure 4). Such a strategy will, therefore, be characterized by a taller (large force) and thinner (short time) active net impulse and a higher rate of force development in the braking phase (20-22, 24, 32).

INSERT FIGURE 4 ABOUT HERE

Propulsion Phase

The fourth CMJ phase is the propulsion phase (12, 24, 32), which has also been referred to as the concentric (17-19) or push-off (18, 30) phase in some studies , whereby athletes forcefully extend their hips, knees and ankles to propel their COM vertically. This phase technically begins when a positive COM velocity is achieved (12, 14, 18) but a velocity threshold of 0.01 m·s^{-1} has been recently used with success to identify the onset of the propulsion phase for large (full squad) data sets (20-22). The force platform sampling frequency and the rate at which the athlete transitions from the braking to propulsion phase will likely determine whether an amortization phase can be identified (time delay between zero and 0.01 m·s^{-1} COM velocity) but as no study has explored this to date, the amortization phase will not be considered in this article. By this definition, the force at the onset of the propulsion phase is determined by the force at the end of the braking phase (presumably minus any force "lost" in the amortization phase) and the peak force attained for each of these phases occur within a very short time of one another (usually towards the very end of the braking phase and the very start of the propulsion phase). The shape of the propulsion force-time curve (certainly during the early part of this phase) will, therefore, likely be influenced by the braking peak force, with a large braking peak force requiring a large propulsion force to be applied quickly to minimize time spent transitioning between phases and to reaccelerate body mass sooner.

The propulsion phase continues through to the instant of take-off (see next section). Plotting the displacement-time curve alongside the force-time curve in this phase is visually useful as it shows how vertical COM displacement becomes positive when it exceeds the zero COM displacement that was set when the athlete was stood upright and still during the weighing phase (Figure 3b). It can be assumed, therefore, that the peak positive COM displacement gained in the propulsion phase reflects the COM displacement achieved through plantarflexing the ankles (Figure 3b), as the athlete should adopt a neutral ankle angle (90°)

during the weighing phase when standing upright. This is sometimes referred to as contact height (difference between height of COM at take-off and standing) (34) and informs one of how much extra COM displacement an athlete generates via a forceful plantarflexion, which may be a limiting factor for some (14). It is also interesting to note that peak COM velocity is attained before rather than at take-off which coincides with the instant at which BW is reached again on the descending aspect of the force-time curve and when zero COM displacement is achieved (Figure 3a). At this point the COM begins to decelerate (12, 24, 32), probably due to the shank and foot segments adding to the effective mass being accelerated at this point, although positive COM displacement continues through to the next phase. Some researchers have split the propulsion phase into three sub-phases (two acceleration sub-phases, between onset of propulsion and when peak COM velocity is attained, and the previously mentioned deceleration sub-phase) which could also be considered (24, 32).

Flight Phase

The fifth CMJ phase is the flight phase, whereby the athlete leaves the force platform with the intention of attaining maximal positive COM displacement (i.e. maximal JH). As eluded to above, the flight phase commences at the instant of take-off (when force falls below a set threshold) and ends at the instant of touchdown (when the athlete contacts the force platform again and force rises above a set threshold). As with the determination of the onset of movement at the beginning of the unweighting phase, many force thresholds have been used to identify take-off and touchdown in the literature. A threshold of force equal to 5 times the standard deviation of flight force (when the force platform is unloaded), taken over a 300-millisecond portion of the flight phase, has been successfully used to identify take-off and touchdown in recent work (20-22). Incorrectly identifying the instant of take-off by as little as 2-3 milliseconds can lead to approximately a 2% variation in velocity and displacement (14), with a 3 millisecond misplacement leading to a 0.9 cm absolute error in JH estimates using the take-off velocity method (recommended 'gold standard': JH = v2 ÷ 2g, where v = velocity and g = gravitational acceleration) (34). In relative error terms, a force threshold of 6 N and 10 N above true zero (when the 0.7 – 2 N signal noise was accounted for) led to a 1% and 1.5% overestimation in JH, respectively (33). These errors, although considered small, can be reduced further by collecting force-time data at a sufficiently high sampling and integration frequency (34) (see above and Table 1). Therefore, one should consider these potential sources of error wisely when collecting and analyzing their force-time data and, again, apply a consistent threshold across trials, sessions and athletes.

INSERT FIGURE 5 ABOUT HERE

At the instant when maximal positive COM displacement is achieved (Figure 5a), which coincides with a momentary COM velocity of zero (Figure 5b), the athlete descends back towards the force platform and the instant at which the selected force threshold is exceeded denotes the instant of touchdown and, thus, the end of the flight phase. It is worth noting in this section that using the duration of the flight phase (i.e. flight time) to estimate JH (18) is based on the assumption that the apex of the jump (peak positive COM displacement)

occurs at half of the duration of the flight phase but this only holds true if COM height is the same at the instant of take-off and touchdown (14). Consequently, any alterations in joint geometry, as may be achieved by flexion of ankles, knees or hips before touchdown, will affect this calculation. It is suggested, therefore, that practitioners and researchers should use the take-off velocity method (impulse-momentum theorem, see above) of estimating JH (25), assuming that they adhere to the aforementioned data collection and analyses criteria, where possible. If the flight time method must be used, then it is important to instruct athletes to avoid flexing ankles, knees and hips during landing. Finally, COM displacement (work-energy theorem) can be used to calculate jump height too (18) if correct data collection and analyses procedures are adopted, as numerical double integration is very sensitive to accurate body mass determination (34).

Landing Phase

The sixth and final CMJ phase is the landing phase, whereby the athlete applies a net impulse that will match the propulsion impulse to decelerate the COM from the velocity at which it contacts the force platform at through to zero. As mentioned for the braking phase, the net impulse required to stop a given mass travelling at a given velocity depends upon the magnitude of the velocity. Landing velocity will mainly depend on JH, with greater JH leading to greater landing velocity. Therefore, for an athlete of a given body mass, a greater landing velocity will require the application of a larger net impulse. Unlike the braking phase, however, there is little need for athletes to decelerate quickly during the landing phase when the CMJ is being tested as single trials. Consequently, athletes are often instructed to "absorb" the landing by flexing the hips, knees, and ankles, thereby applying a net impulse characterized by a smaller force being applied over a longer duration (similar to that shown for the braking phase in Figure 4). Athletes who are not given, or do not adhere to, this instruction will produce larger peak landing forces. The landing phase is considered to have ended when COM velocity reaches zero again (Figure 6a) which coincides with the peak negative COM displacement achieved during this phase (Figure 6b). The landing phase can also be split into two sub-phases (impact [between touchdown and peak force] and stabilizing [between peak force and peak negative COM displacement]) for additional information about landing strategy/ability.

INSERT FIGURE 6 ABOUT HERE

Practical Applications

Six key CMJ phases can be identified from force-time curves (weighing, unweighting, braking, propulsion, flight, and landing – see Table 2) but accurate determination of these phases depends on sufficient sampling and numerical integration frequency, a precise determination of BW and the force and velocity thresholds used to determine the start and end of each phase. It is essential that these factors are considered by researchers and practitioners to ensure that these CMJ phases can be correctly identified and thus yield valid information about athletes' neuromuscular and SSC capabilities. Researchers and practitioners can use the information presented here, therefore, to guide their own analyses and interpretation of

athletes' CMJ force-time curves. Comprehensive discussion of the application of these data are beyond the scope of this article. However, understanding the contribution of each phase to CMJ performance enables practitioners to hone in on specific areas that may require development, thus providing far greater insight into the athlete's capacity to accelerate their body mass. Specifically, practitioners should focus on gaining an understanding of what the shape of the force-time curve means (8), and how the forces applied during and the length of the different phases can be altered, both through coaching and specific training. Finally, it is suggested that these simple, but relatively obvious, names for the different CMJ phases should be used by S&C researchers and practitioners to promote consistency and clarity across the profession.

INSERT TABLE 2 ABOUT HERE

References

1.   Anderson FC and Pandy MG. Storage and utilization of elastic strain energy during jumping. *J Biomech* 26: 1413-1427, 1993.
2.   Beckham G, Suchomel T, and Mizuguchi S. Force plate use in performance monitoring and sport science testing. *New Stud Athlet* 29: 25-37, 2014.
3.   Cormie P, McBride JM, and McCaulley GO. Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *J Appl Biomech* 24: 112-120, 2008.
4.   Cormie P, McBride JM, and McCaulley GO. Power-Time, Force-Time, and Velocity-Time Curve Analysis of the Countermovement Jump: Impact of Training. *J Strength Cond Res* 23: 177-186, 2009.
5.   Dowling J, J. and Vamos L. Identification of Kinetic and Temporal Factors Related to Vertical Jump Performance. *J Appl Biomech* 9: 95-110, 1993.
6.   Eagles AN, Sayers MGL, Bousson M, and Lovell DI. Current Methodologies and Implications of Phase Identification of the Vertical Jump: A Systematic Review and Meta-analysis. *Sports Med* 45: 1311-1323, 2015.
7.   Ebben W, Flanagan E, and Jensen R. Gender similarities in rate of force development and time to takeoff during the countermovement jump. *J Exerc Physiol Online* 10: 10-17, 2007.
8.   Garhammer J and Gregor R. Propulsion forces as a function of intensity for weightlifting and vertical jumping. *J Appl Sport Sci Res* 6: 129-134, 1992.
9.   Gathercole R, Sporer B, Stellingwerff T, and Sleivert G. Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue. *Int J Sports Physiol Perform* 10: 84-92, 2015.
10.   Gutiérrez-Dávila M, Amaro FJ, Garrido JM, and Rojas FJ. An analysis of two styles of arm action in the vertical countermovement jump. *Sports Biomech* 13: 135-143, 2014.
11.   Hara M, Shibayama A, Takeshita D, Hay DC, and Fukashiro S. A comparison of the mechanical effect of arm swing and countermovement on the lower extremities in vertical jumping. *Hum Mov Sci* 27: 636-648, 2008.
12.   Hatze H. Validity and reliability of methods for testing vertical jumping performance. *J Appl Biomech* 14: 127-140, 1998.
13.   Jidovtseff B, Quievre J, Nigel H, and Cronin J. Influence of jumping strategy on kinetic and kinematic variables. *J Sports Med Phys Fitness* 54: 129-138, 2014.

14.   Kibele A. Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *J Appl Biomech* 14: 105-117, 1998.

15.   Kurokawa S, Fukunaga T, Nagano A, and Fukashiro S. Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo. *J Physiol Physiol* 95: 2306-2314, 2003.

16.   Laffaye G, Wagner PP, and Tombleson TIL. Countermovement Jump Height: Gender and Sport-Specific Differences in the Force-Time Variables. *J Strength Cond Res* 28: 1096-1105, 2014.

17.   Lake JP, Mundy PD, Comfort P, McMahon JJ, Suchomel TJ, and Carden P. The Validity of Portable Force Plate Countermovement Vertical Jump Reactive Strength and Force-time Characteristics, in: *40th Annual National Conference and Exhibition of the National Strength and Conditioning Association*. Las Vegas, NV, 2017.

18.   Linthorne NP. Analysis of standing vertical jumps using a force platform. *Am J Phys* 69: 1198-1204, 2001.

19.   McMahon JJ, Jones PA, Dos'Santos T, and Comfort P. Influence of Dynamic Strength Index on Countermovement Jump Force-, Power-, Velocity-, and Displacement-Time Curves. *Sports* 5: 72, 2017.

20.   McMahon JJ, Jones PA, Suchomel TJ, Lake J, and Comfort P. Influence of Reactive Strength Index Modified on Force- and Power-Time Curves. *Int J Sports Physiol Perform*, Publish Ahead of Print.

21.   McMahon JJ, Murphy S, Rej SJ, and Comfort P. Countermovement Jump Phase Characteristics of Senior and Academy Rugby League Players. *Int J Sports Physiol Perform*, Publish Ahead of Print.

22.   McMahon JJ, Rej SJ, and Comfort P. Sex Differences in Countermovement Jump Phase Characteristics. *Sports* 5: 8, 2017.

23.   McMahon JJ, Ripley NJ, and Rej SJ. Effect of modulating eccentric leg stiffness on concentric force-velocity characteristics demonstrated in the countermovement jump. *J Sports Sci* 34: S19, 2016.

24.   Mizuguchi S, Sands WA, Wassinger CA, Lamont HS, and Stone MH. A new approach to determining net impulse and identification of its characteristics in countermovement jumping: reliability and validity. *Sports Biomech* 14: 258-272, 2015.

25.   Moir GL. Three Different Methods of Calculating Vertical Jump Height from Force Platform Data in Men and Women. *Meas Phys Educ Exerc Sci* 12: 207-218, 2008.

26.   Owen NJ, Watkins J, Kilduff LP, Bevan HR, and Bennett MA. Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump. *J Strength Cond Res* 28: 1552-1558, 2014.

27.   Peterson Silveira R, Stergiou P, Carpes FP, Castro FAdS, Katz L, and Stefanyshyn DJ. Validity of a portable force platform for assessing biomechanical parameters in three different tasks. *Sports Biomech* 16: 177-186, 2016.

28.   Rice PE, Goodman CL, Capps CR, Triplett NT, Erickson TM, and McBride JM. Force- and power-time curve comparison during jumping between strength-matched male and female basketball players. *Eur J Sport Sci* 17: 286-293, 2017.

29.   Riggs MP and Sheppard JM. The relative importance of strength and power qualities to vertical jump height of elite beach volleyball players during the counter-movement and squat jump. *J Hum Sport Exerc* 4: 221-236, 2009.

30.   Samozino P, Morin J-B, Hintzy F, and Belli A. A simple method for measuring force, velocity and power output during squat jump. *J Biomech* 41: 2940-2945, 2008.

31.   Sánchez-Sixto A, Harrison A, and Floría P. La importancia de la profundidad del contramovimiento en el ciclo estiramiento-acortamiento / Importance of Countermovement Depth in Stretching and Shortening Cycle Analysis. *Revista*

Internacional de Medicina y Ciencias de la Actividad Física y el Deporte, Publish Ahead of Print.

32. Sole CJ, Mizuguchi S, Sato K, Moir GL, and Stone MH. Phase characteristics of the countermovement jump force-time curve: A comparison of athletes by jumping ability. *J Strength Cond Res*, Publish Ahead of Print.

33. Street G, McMillan S, Board W, Rasmussen M, and Heneghan JM. Sources of error in determining countermovement jump height with the impulse method. *J Appl Biomech* 17: 43-54, 2001.

34. Vanrenterghem J, De Clercq D, and Cleven PV. Necessary precautions in measuring correct vertical jumping height by means of force plate measurements. *Ergon* 44: 814-818, 2001.
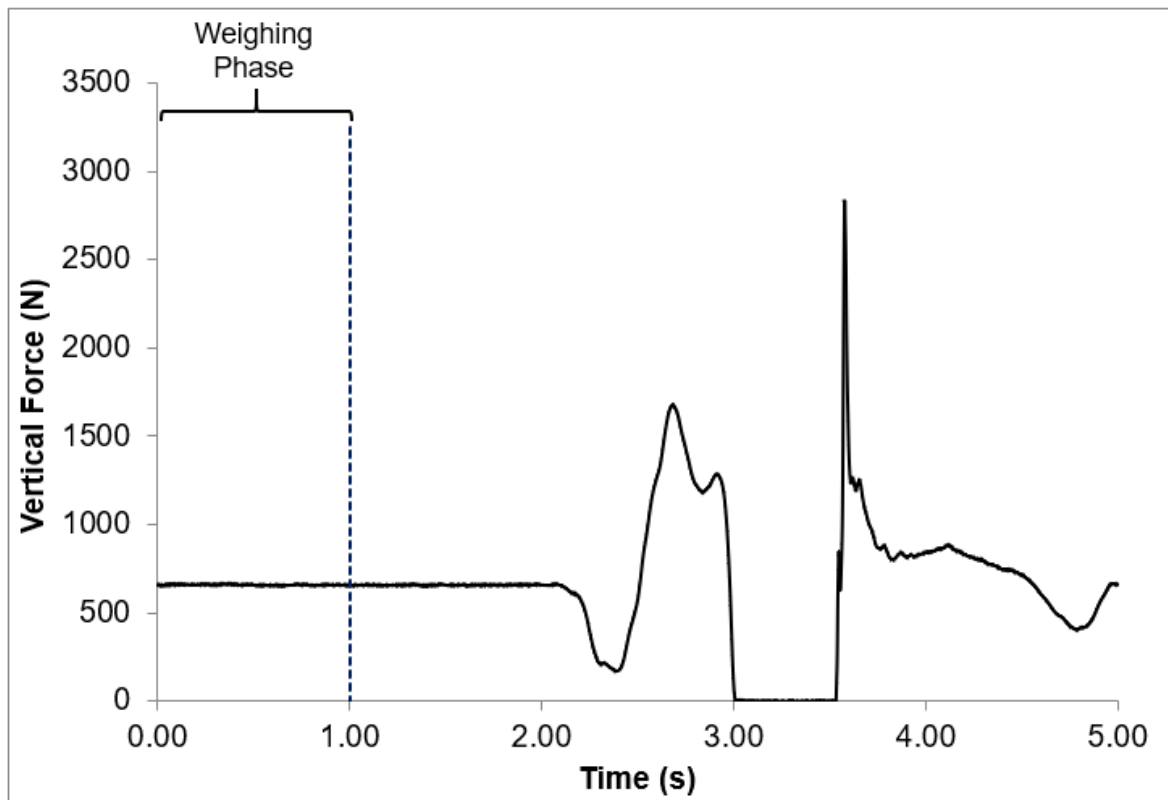
Figures

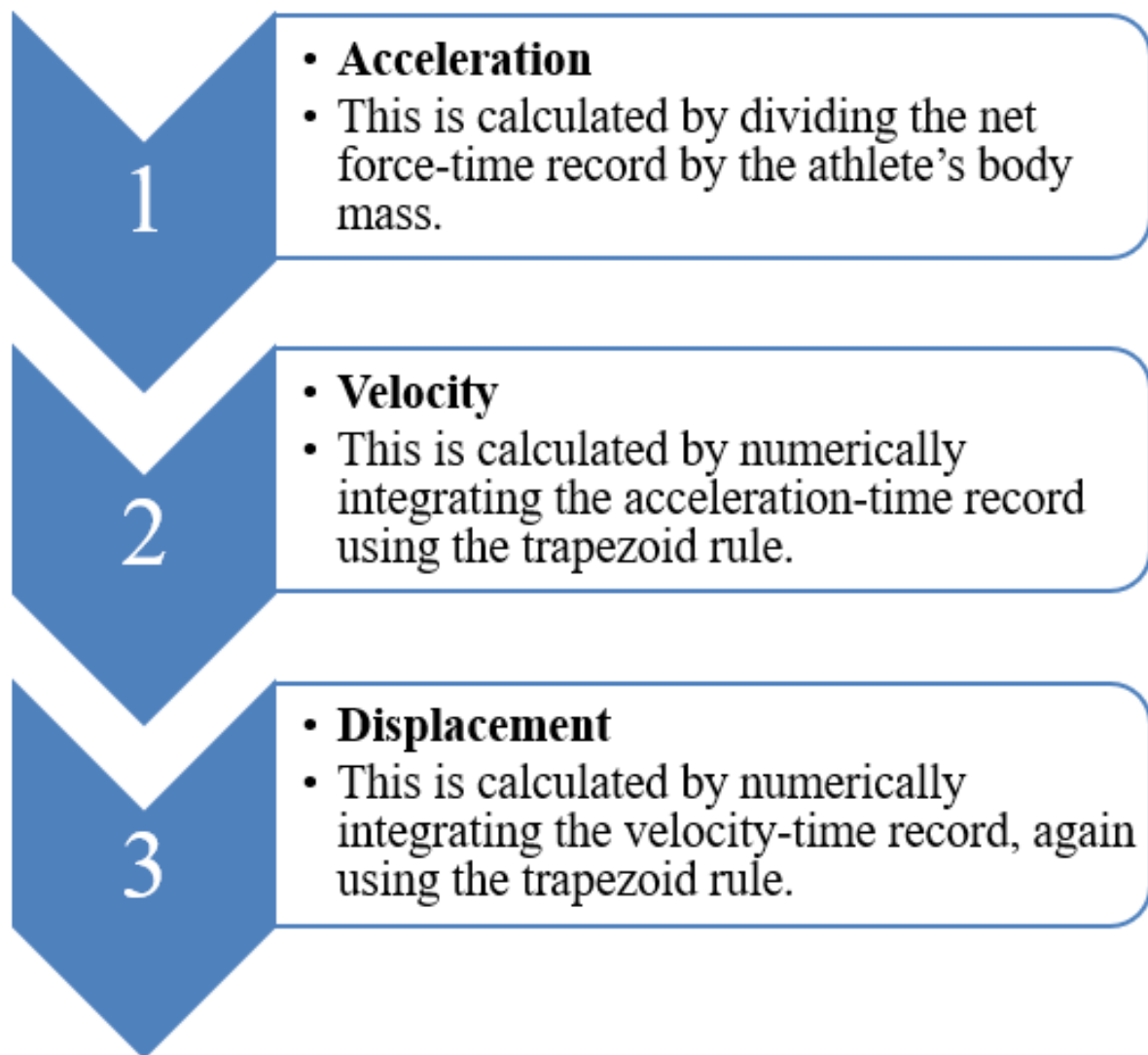**Figure 1:** Typical force-time record for a countermovement jump with the weighing phase highlighted.

1
- **Acceleration**
- This is calculated by dividing the net force-time record by the athlete's body mass.

2
- **Velocity**
- This is calculated by numerically integrating the acceleration-time record using the trapezoid rule.

3
- **Displacement**
- This is calculated by numerically integrating the velocity-time record, again using the trapezoid rule.

Figure 2: A brief description of how acceleration, velocity and displacement are derived from the CMJ net force-time record, a process commonly referred to as forward dynamics. *Please note that the net force acting on the athlete's center of mass is calculated by subtracting the athlete's bodyweight from the original vertical ground reaction force record.*
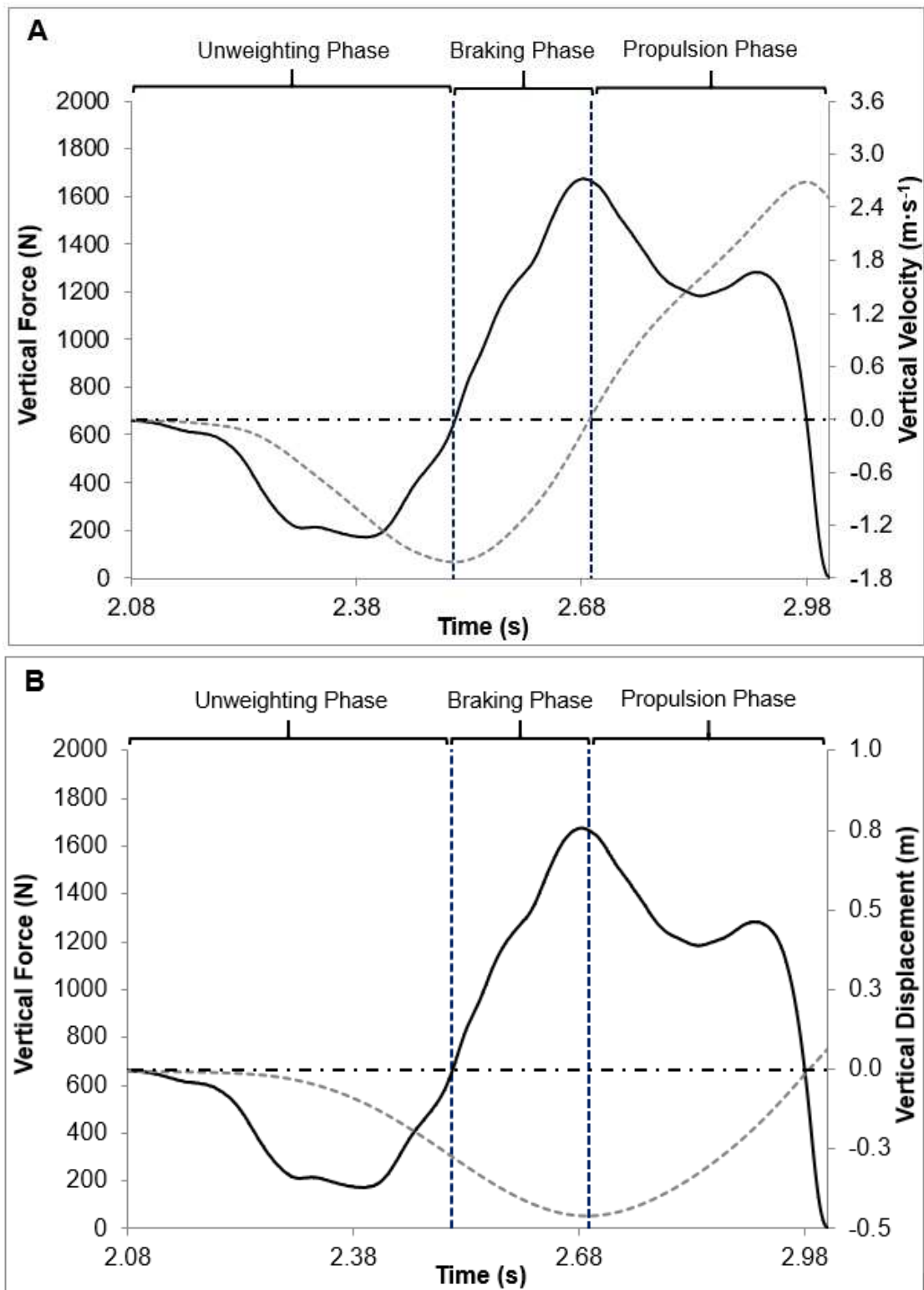
Figure 3: Typical force-time (solid black line) record for a countermovement jump between the onset of movement and take-off, with the associated velocity-time (dotted grey line in graph A) and displacement-time (dotted grey line in the graph B) presented and the unweighting (negative acceleration and negative direction), braking (positive acceleration but negative direction) and propulsion (positive acceleration [until force is below bodyweight] and positive direction) phases highlighted. The dash-dot black line represents bodyweight.
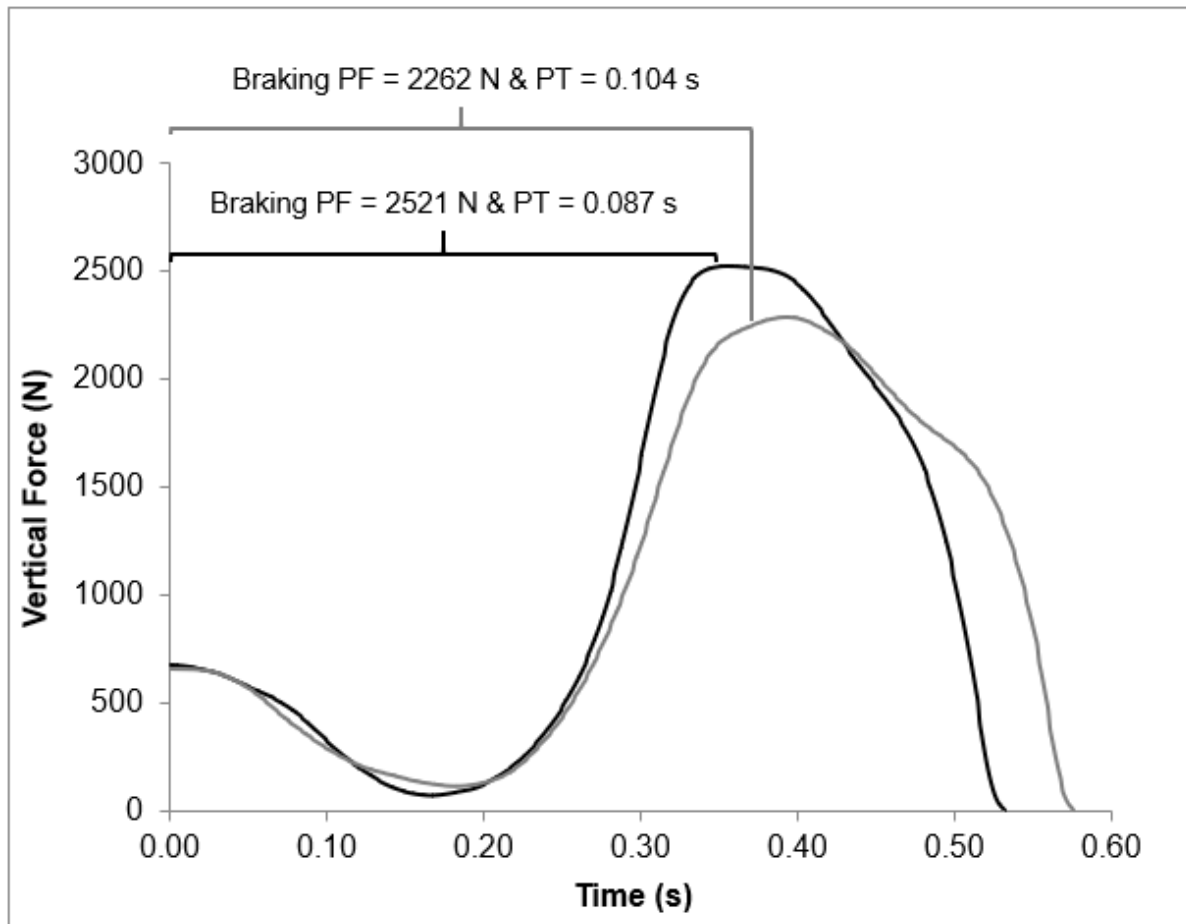
Figure 4: Example force-time record for a countermovement jump, between the onset of movement and take-off, performed by the same athlete (body mass = 71.8 kg) who achieved an almost identical unweighting and braking phase net impulse 95-96 N·s but whose braking phase net impulse was characterized by a larger force and shorter time in trial 1 (black line) vs. trial 2 (grey line). PF = peak force and PT = phase time.
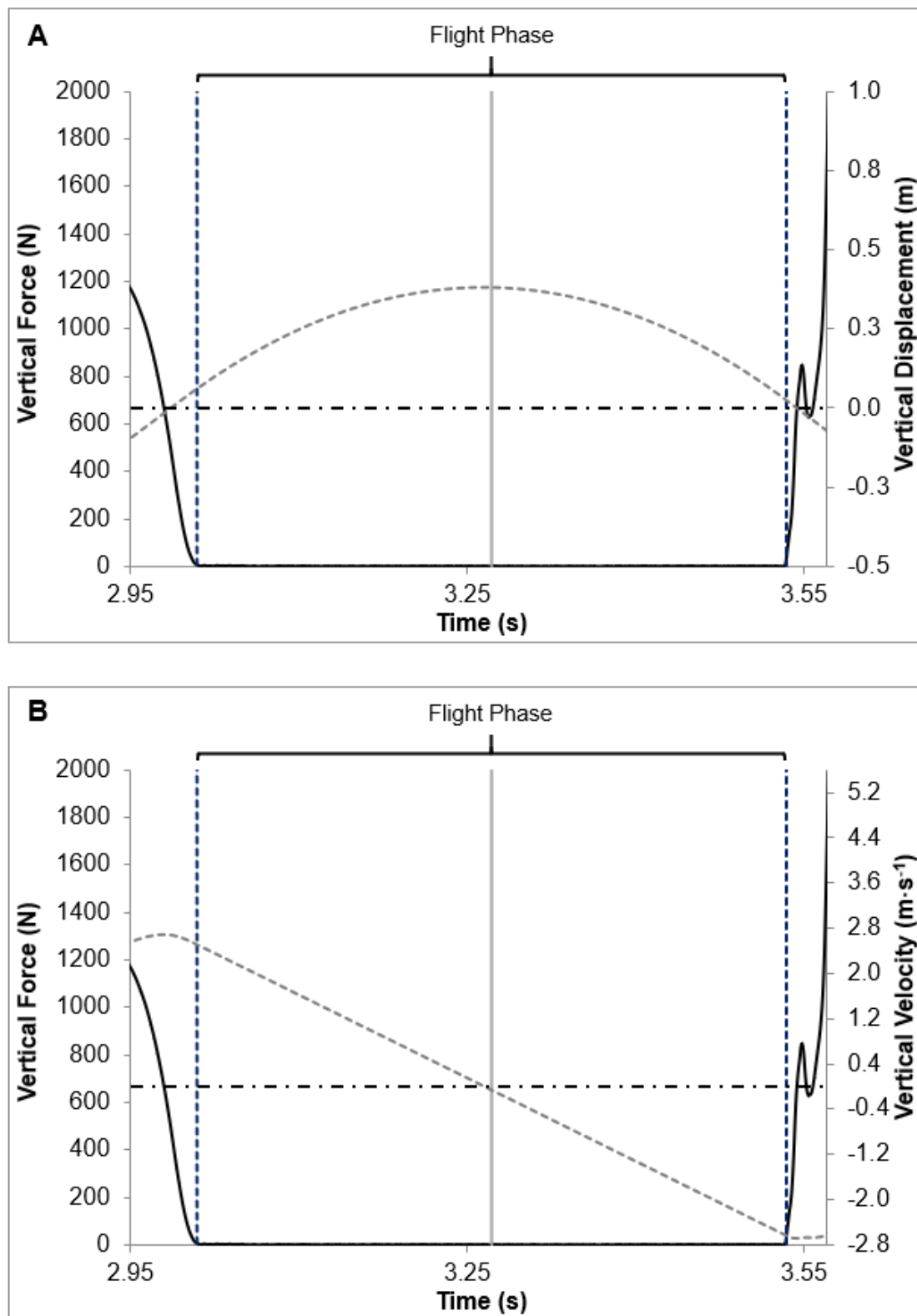
Figure 5: Typical force-time (solid black line) record for a countermovement jump between just before and after the instants of take-off and touchdown, respectively, with the associated displacement-time (dotted grey line in the graph A) and velocity-time (dotted grey line in graph B) presented and the flight phase highlighted. The dash-dot black line represents bodyweight and the vertical grey line represents mid-point of the flight phase where peak center of mass displacement and zero center of mass velocity is achieved.
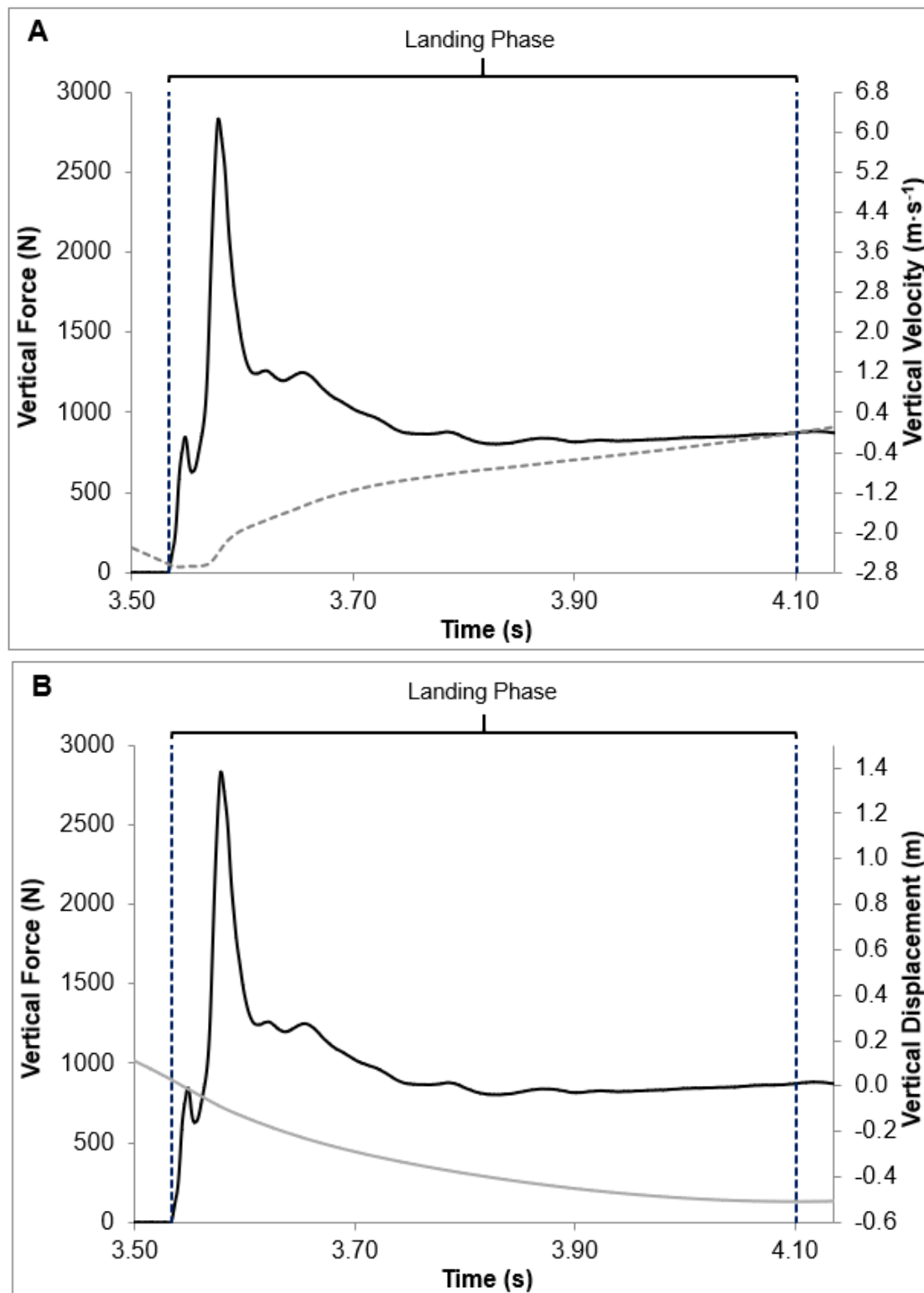
Figure 6: Typical force-time (solid black line) record for a countermovement jump between just before and after the instants of touchdown and end of the landing phase, respectively. The associated velocity-time (dotted grey line in graph A) and displacement-time (dotted grey line in the graph B) are presented and landing phase highlighted.

Tables

Table 1: A summary of the data collection and analyses procedures used to acquire the athlete's* countermovement jump trials presented in this article.

Task Instructions	Rationale
Stand upright[1] with arms akimbo[2] and remain as still as possible[3] until given the command "jump"	[1]Center of mass displacement throughout the jump is calculated in relation to standing center of mass height [2]Arm swing can induce small alterations to velocity and height of the center of mass at take-off (10) and negatively (albeit slightly) impact data reliability (11) [3]A still period of at least 1 second before commencing the jump is required to ascertain bodyweight and the onset of movement threshold (26)
On the command "jump", rapidly[1] squat to your preferred depth[2] by flexing your hip, knees and ankles	[1]A rapid squat is encouraged to stimulate the stretch-shortening cycle [2]It is difficult to standardize countermovement depth (31) and altering this will affect 'natural' force-time characteristics (13, 23)
At the bottom of the squat, immediately[1] jump as fast and as high[2] as possible by rapidly extending your hip, knees and ankles	[1]Minimal pause at the bottom of the squat (termed the amortization phase) is encouraged to help prevent a reduction in stretch-shortening cycle utilization [2]Attaining a greater propulsion velocity by applying a greater net impulse will lead to a greater jump height
Upon landing, absorb[1] the forces by flexing your hip, knees and ankles, again to achieve your preferred squat depth	[1]Stiffer landings lead to larger peak forces which may place the athlete at undue risk of sustaining a musculoskeletal injury
Data Collection	**Rationale**
The force platform used was a portable piezoelectric Kistler[1] type 9286AA (Kistler	

Instruments Inc., Amherst, NY, USA) which was placed on flat ground and zeroed[2] before each trial	[1]Kistler produce research-grade force platforms capable of detecting rapid changes in force production [2]It is essential to zero the force platform before each CMJ trial to reduce signal noise
Force-time data for each trial were sampled at 1000 Hz[1] for 5 seconds	A minimum sample frequency of 1000 Hz has been recommended for CMJ force-time assessments (26, 33)
Data Analyses**	**Rationale**
Raw[1] vertical force-time data were exported for further analyses in a customized Microsoft Excel spreadsheet[2] (version 2016, Microsoft Corp., Redmond, WA, USA)	[1]Filtered force-time data can lead to underestimations of CMJ height (33) [2]Commercial software packages can automate most calculations, but this can also be done using Microsoft Excel
Numerical integration (see Figure 2 for procedural description) using the trapezoid rule[1] began at the onset of data collection[2] at a frequency of 1000 Hz[3]	[1]The trapezoid method of integration is most commonly applied to CMJ force-time data and although it can lead to a $\leq 0.3\%$ underestimation of CMJ height, higher order integration methods (e.g. Simpson's rule) do not vastly improve accuracy (14, 18) [2]Street et al. (33) showed that integrating force-time data anywhere from 0-1.5 seconds before the onset of movement had no meaningful effect on CMJ height [3]Integration frequencies of at least 200 Hz have been suggested (34), with 1000 Hz (the highest frequency tested) leading to the smallest errors in center of mass displacement

*The athlete tested was a male collegiate soccer player aged 22 years, with a body mass of 67.5 kg and a standing height of 1.8 m; **Data analyses as it relates to countermovement jump (CMJ) phase identification is not included in this table as it forms the main discussion points of the present article.*

Table 2: A brief description of the key phases of the countermovement jump force-time curve.

Phase	Description
Weighing	Begins at the onset of data collection, when the subject is stood upright and still, and lasts for at least one second
Unweighting	Begins at the onset of movement (when force falls below a set force threshold) and ends when bodyweight is reached again, which coincides with peak negative center of mass velocity
Braking	Begins at the end of the unweighting phase and ends when center of mass velocity equals zero (the momentary pause at the bottom of the countermovement)
Propulsion	Begins when center of mass velocity becomes positive and ends at take-off (when the subject leaves the force platform)
Flight	Begins at the instant of take-off (when force falls below a set force threshold) and ends at the instant of touchdown (when force rises above a set force threshold)
Landing	Begins at the instant of touchdown and ends when center of mass velocity equals zero