Developing Powerful Athletes, Part 1: Mechanical Underpinnings

Anthony N. Turner, PhD,1 Paul Comfort, PhD,2 John McMahon, PhD,2 Chris Bishop, MSc,1 Shyam Chavda, MSc,1 Paul Read, PhD,3,4 Peter Mundy, PhD,5 and Jason Lake, PhD6
1London Sports Institute, Middlesex University, Greenslands Lane, United Kingdom; 2University of Salford, School of Health and Society, Salford, United Kingdom; 3Aspetar Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar; 4Centre for Exercise and Sports Science Research, Edith Cowan University, Joondalup, Australia; 5Coventry University, Coventry, United Kingdom; and 6Chichester Institute of Sport, University of Chichester, Chichester, United Kingdom

ABSTRACT
This review will revisit practitioner understanding of the development of power, before outlining some of the key mechanical parameters that contribute to power development. This understanding will help with planning and periodization of strength and power training, which is explored in part 2 of this 2-part review. This review (part 1) discusses the force-time and force-velocity curve and addresses recent criticism in using terms such as power, rate of force development, and explosiveness, over impulse. These terms are distinguished mechanically and conceptually for the benefit of the scientist and coach, and are essential for effective sharing of data and practice.

INTRODUCTION
The nature of sport is such that athletes are generally required to execute their motor skills, including jumping, kicking, lunging, and throwing, as quickly as possible over a given range of motion (ROM), underpinning these movements with high levels of force. Rapid acceleration is required to hit a ball over long distances, outjump opponents, and physically outperform them when required. Consequently, developing powerful athletes is often a strength and conditioning (S&C) coach’s goal. Understanding the mechanical definition of power, and its relationship to the force-time characteristics of sporting movements and training drills, can assist the S&C coach in developing periodized training plans. Furthermore, analyzing the graphical representation of their data, from different assessment methods, can facilitate this understanding further. Here, we refer to the (a) force-time curve and (b) force-velocity curve.

We will start with an explanation of mechanical terms, in the context of training for power, given the criticism that terms such as “power” and “explosiveness” have received when used by the S&C community (9,15,22,23); this in turn is likely to have generated confusion among S&C coaches, and thus clarification is required. Equally, because the authors of these critical reviews do indeed make valid claims, their points must be elaborated on and considered when training and testing athletes. As they explain, this is essential if the sharing of data and practices among colleagues and across disciplines is to be effective.

MECHANICAL DEFINITIONS AND PRACTICAL APPLICATIONS
First, we should note that although the term “power” is commonly accepted in the S&C community, the misuse of this mechanical variable has been criticized (9,15,22,23). In brief, “power” is often expressed as a “generic neuromuscular or athlete performance characteristic” rather than as an application of the actual mechanical definition. Mechanically, power is the work performed per unit of time (the rate of doing work), which can also be calculated by multiplying force by velocity (Table 1 for formulas). Equally, describing powerful movements as “explosive” has caused concern as nothing explodes (23). However, it is an excellent coaching term that conveys key aspects of what the practitioner typically wants the athlete to achieve during power training, that is, move the given load as fast as possible. Therefore, based on the context in which terms are used, as well as the desired outcome, coaches must clearly differentiate the use of such terms.

Second, it has been contested that given the fact that the impulse-momentum...
relationship perfectly describes the requirements for "powerful" movements, strength and conditioning coaches should focus on examining net impulse and more importantly, its underpinning components: net force and time (duration of force application) (9,22,23). For example, we typically aim to calculate an athlete’s impulse-momentum theorem (Newton’s second law of motion) (9,22,23). For example, when examining an athlete’s jump data, when the impulse-momentum theorem (Newton’s second law of motion), which can be used to calculate jump height, is not often assessed or reported (the reader should note that takeoff velocity is derived from net propulsion impulse divided by body mass, with jump height subsequently calculated from takeoff velocity). Finally, as we note in our later analysis of Figures 1 and 2, the impulse over a given period (usually up to 0.3 seconds), or the area under the force-time curve, is comparable to rate of force development (RFD). This is because when time is constrained by the use of a given epoch, only force output can influence the outcome of both metrics. However, although both net impulse and RFD include force and time, only net impulse is directly related to the change of velocity of the object of interest (12).

It is interesting to consider why S&C coaches typically choose not to report impulse and instead concentrate on training and testing power and RFD, adopting terms such as “explosive” on route. Perhaps, the answers lie in the communication of these terms with athletes and the impact that coaching cues have on athlete learning and retention (21). For example, rather than asking an athlete to “explode,” which is a very clear and conceptual term, asking them to be “highly impulsive” would likely generate confusion. Equally, referring to an athlete as “impulsive” in itself conveys a different message.

Furthermore, asking athletes to pull or push against the bar as quickly as possible so as to assess their RFD seems to explicitly convey the focus and importance of the test. Telling them to do so because we want to analyze the area under the force-time curve or impulsivity, perhaps, may not resonate so well. These terms, if not explicit in their meaning (such as be “powerful” and “explode”), provide a conceptual guide to describe the test and the relevance of its data (e.g., “RFD”). Clearly, our intention is not to discourage the use of these terms (acknowledging that the authors routinely use them), but instead it is to highlight the fact that like many other words, they have different interpretations (here, a theoretical or mechanical definition, and a practical, coaching-oriented definition). This distinction is important to enable the unambiguous sharing of data and practice.

<table>
<thead>
<tr>
<th>Term</th>
<th>Practical term</th>
<th>Mechanical definition</th>
<th>Mathematical formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Generic neuromuscular or athlete performance characteristic</td>
<td>Work performed per unit of time</td>
<td>Power = work/time or P = W/t; where work = force × displacement or F × s</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>And, because (F × s)/time is the same as force × velocity, P = force × velocity or F × v</td>
</tr>
<tr>
<td>Explosive</td>
<td>“Push/pull hard and fast”</td>
<td>Referring to power if the athlete is “driving” forcefully over a set range of motion, or impulsive, if “driving” forcefully within a set period</td>
<td>Power (as above) Impulse = force × time or J = F × t (Newton’s second law of motion)</td>
</tr>
<tr>
<td>Rate of force development (RFD)</td>
<td>“Explosive strength” or the ability to “push/pull hard and fast”</td>
<td>Change in force over given period</td>
<td>RFD = ΔF/Δtime Δ = change in</td>
</tr>
<tr>
<td>Epoch defined impulse</td>
<td>“Explosive strength” or the ability to “push/pull hard and fast”</td>
<td>Impulse (or rather area under the curve) over a given period</td>
<td>Impulse = ΔF × Δtime Δ = change in</td>
</tr>
<tr>
<td>Force</td>
<td>Strength</td>
<td>Ability to accelerate a mass (Newton’s 1st law of motion)</td>
<td>Force = mass × acceleration or F = m × a</td>
</tr>
<tr>
<td>Impulse–momentum theorem</td>
<td>Momentum is not often used as a practical term but may describe someone able to change the speed they are moving at.</td>
<td>Because mass typically remains constant in an S&amp;C context, impulse is directly proportional to the change in velocity</td>
<td>p = F × t = m × Δv</td>
</tr>
</tbody>
</table>

P = power; W = work; t = time; F = force; s = displacement; v = velocity; J = impulse; Δ = change; m = mass; a = acceleration; p = momentum. |
time and ROM (or rather the distance ing motor skills that are constrained by treated in Figure 1). This suggests that dur-
time to achieve this than others (illus-
ated throughout this article and includes mechanical and practical terms cov-
ered throughout this article and includes key mechanical and practical terms cov-
ed throughout this article and includes all associated formulas.

THE FORCE-TIME CURVE
The first curve we will analyze is the force-time curve (Figure 1), which reveals that maximum isometric force is not instantaneously developed, taking as much as 0.6–0.8 seconds to develop. The majority of athletic movements, however, occur within <0.3 seconds.

Figure 1. Force-time curve reveals that maximum force is not instantaneously developed, taking as much as 0.6–0.8 seconds to develop. The majority of athletic movements, however, occur within <0.3 seconds.

It should also be noted that given these different force-time profiles, the training focus for each athlete will be different and is covered in part 2 of this review.

IMPULSE AND RATE OF FORCE DEVELOPMENT
Figures 1 and 2 describe the ability of an athlete to rapidly produce force (impulse capacity or RFD depending on your preference; or explosive strength if communicating with athletes). Given the sig-
nificance of the initial portion of the force-time curve—that is, up to a time point considered to correspond with a particular sporting movement (e.g., 0.25 or 0.30 seconds)—it is advisable to calculate net impulse and RFD across designated epochs. To calculate impulse during an IMTP for example, one would calculate the change in force applied to the force platform by the athlete up to the time point of interest, and then multiply that change in force by the time over which it occurred. Conversely, RFD is calculated as the change in force divided by the change in time. Again, using the example of the IMTP, this would mean recording the force generated up to the time point of interest then dividing it by time. Impulse will produce a value in Newton seconds (Ns), whereas RFD will produce a value in Newtons per second (N·s⁻¹). The subtle differences between them can also be seen in Figure 3, where it can be noted that their calculations (i.e., area under the curve vs. the linearly increasing force between designated time points) can result in slightly different, albeit highly correlated, results. It should also be pointed out that dividing net impulse by the athlete’s mass would provide a measure of their velocity capacity (potential for acceleration if performing a dynamic task). Of course, the athlete would be constrained by the task (isometric), but theoretically this indicates how fast one could move if they were able to let go of the bar at the time point of interest. This means that the greater the impulse one can apply during this sort of task, the greater their velocity capacity, and this could have important implications for sporting performance.

Theoretically, RFD and impulse at the corresponding epoch are quantifying among colleagues; as S&C practitioners, we must regularly alternate between sci-
cence and coaching. In summary, context determines if their use is correct. Telling an athlete, you want them to “explode” during a movement is acceptable, but such terminology should not be used within the scientific literature, unless describing the instructions given to ath-
etes. When undertaking scientific analy-
asis, it is important to forgo colloquial terms for mechanical ones. Table 1 summarizes key mechanical and practical terms covered throughout this article and includes all associated formulas.

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similar characteristics, the ability to apply force during given periods (again because time is constrained by a given epoch, both RFD and impulse are only influenced by force). However, because impulse is directly proportional to the change in momentum, and typically this refers to the change in velocity (i.e., acceleration) of a constant mass (athlete, implement, or athlete/implement system), it may provide a more complete picture of an athlete’s capacity to apply force during given periods, in addition to providing an indication to accelerate from given start points because it provides a direct performance outcome.

It is also important to consider the error associated with different variables such as RFD and impulse. Problems inherent to both include the determination of force onset (i.e., the threshold used) and factors associated with the sampling, filtering, and smoothing of the raw data; for more information on this within isometric assessments, see the study by Comfort et al. (4). Furthermore, the calculation of each metric also affects error, but potentially more so for RFD. For example, when calculating RFD, the force identified at the designated time point is divided by time (e.g., 0.25 seconds). Therefore, any error in the identification of this instantaneous time point is amplified. For example, if \( \Delta F = 1000 \text{ N} \), then RFD = 4000 N s\(^{-1}\) (i.e., \( 1000 \times 0.25 \)), thus any error contained within the determination of \( \Delta F \) would, in this case, be multiplied by 4. However, because impulse is calculated as the area under the curve, signal noise is suppressed. For example, if force was again applied over a duration of 0.25 seconds, then impulse would equal the integral of force multiplied by 0.25. Thus, the error contained with the calculation of force is, in this example, now quartered. These calculations highlight the difference in signal noise (or error) generated when using differentiation (which examines the rate of change of a curve) versus integration (which sums small discrete areas under the curve to calculate the total area) based on calculus; the former typically increases error, whereas the latter decreases it. All that said, more studies are showing the reliability of RFD and its association with performance, and readers should familiarize themselves with these when wanting to calculate RFD; for more information on this, refer to the study by Haff et al. (5).

As a final note, and considering the aforementioned error inherent with these calculations, simply identifying force at specific time points (e.g., 0.1 seconds or whatever epoch best corresponds to a fundamental sports motor skill such as those highlighted in Table 2) is another metric that may be reported (3,7,19) and compared to previous scores to determine if change has occurred. We would speculate that this metric will continue to grow in popularity and become far more used in research and practice. This is because if force at a specific time point increases, then impulse and RFD across the same epoch must have also increased. Furthermore, because only force is being reported (and thus no calculations are required), no error is introduced through the respective calculations, and subject only to the identification of the onset of force production as detailed above. In support of this statement, this method of purely force identification at specific time points has shown good levels of reliability (intraclass correlation coefficients = 0.95–1.00 and 0.921–0.968), with low levels of variance (CV = 2.3–2.7% and 6.2–8.0%) (5).

### POWER, IMPULSE, AND THE WORK-ENERGY THEOREM

In the context of jumping, there is theoretically a direct cause and effect relationship between the work performed on the system center of mass (CM) and the height jumped (work-energy theorem). Similarly, there is theoretically a direct cause and effect relationship between the impulse applied to the system CM and the height jumped (impulse-momentum theorem). Changes in the system’s CM momentum are due to the net impulse applied to the system CM, which depends on the time over which the net force is applied. Conversely, kinetic energy of the system CM changes when work is performed on the system CM, which depends on the displacement over which the net force is applied. An increase in the work performed and the impulse applied would result in an increase in jump height. Therefore, as the impulse-momentum relationship is well accepted within the literature, in this section, we help to clarify the cause and effect relationships of the work-energy theorem.

Maintaining the context of jumping, the work-energy theorem states that the net work performed on an object is equal to the change in kinetic energy and is written as:
It is important to note that this theorem can be expanded to include other forms of energy, but for the sake of brevity has been constrained to kinetic energy. When under the influence of a net force, the system CM accelerates as work is done on it. Given that the displacement over which the propulsion phase of jumping occurs is constrained by human anatomy (i.e., leg-length), greater work (which is now only influenced by the force applied) performed on the system CM results in a shorter propulsion phase duration (i.e., time), as the pushoff phase is performed at a greater average velocity (i.e., velocity = displacement divided by time, with displacement in this example constrained). Therefore, average power output, which is the rate at which work is performed over the propulsion phase of jumping (remember that power equals $F \times s / t$, increases in line with increases in work, assuming displacement is constrained and optimized. In essence, the greater the work (or KE), the greater the power output and the jump height. In this scenario, power output possesses a cause and effect relationship with performance, in this case to jump height. For a worked example of the work-energy theorem and counter-movement jump (CMJ) performance, readers can refer to the study by Linthorne (11).

So, for the CMJ, or a series of squat jumps in which propulsive displacement remains the same (e.g., starting from a fixed knee angle of 90 degrees), increases in jump height would be matched by increases in power. However, let us now consider the scenario whereby we are measuring an athlete's CMJ height under progressive loads, for example, progressing from bodyweight (BW) to BW + 30 kg, BW + 50 kg.
and finally BW + 80 kg. In this example, the changes (reductions) in jump height will no longer perfectly align to the changes (also reductions) in power, with the reasons behind this going some way in explaining why jump height has recently fallen out of favor with the S&C community, who now instead see the process (i.e., the jump strategy) as a far better performance indicator than the output (i.e., jump height). Anecdotally, we would have all noted that as load increases during a CMJ, the athlete’s jump strategy will change to compensate. That is, under heavier loads, athletes may perform a greater dip or countermovement, in which they lower their CM further, thereby increasing the ROM (and thus work) and time over which they can apply force (to overcome a progressively heavier system mass). Under these conditions, where propulsive displacement increases with load and thus differs between conditions, the relationship between power and jump height weakens. Couple this with the fact that jump height is determined by velocity at takeoff, so if distance increases along with time, and if velocity is distance divided by time, then velocity will continually decrease with increases in system mass. Thus, the disparity between jump height and power is a consequence of power being a product of force and velocity, and in this example, force potentially compensating for the decrease in velocity thus reducing the loss of power output. Finally, and just to reiterate our earlier point, if we now constrain displacement, that is, the countermovement was controlled or they performed a squat jump from a set knee angle, across these various loaded conditions, then jump height and power would again be highly correlated. However, in doing so, we must be mindful that this may reduce the ecological validity of the test and is thus a tradeoff we must be aware of when constraining displacement so that we can define power from jump height.

Now we must turn to another pertinent area within this context, and one which centers on the question of whether S&C coaches should be reporting impulse (or work) when testing athletes (rather than power), and if we should, should they be using training loads that maximize net pushoff impulse, rather than those that maximize power output? The answer to this is perhaps best demonstrated by Mundy et al. (14) who profiled athletes across a series of progressively loaded jumps. Their study found that net impulse during the CMJ continually increased from an unloaded condition through to a 75% body mass (BM) loaded condition, at which point it started to decrease up until the athlete was only just able to jump (100% BM condition). These results can be explained by noting that as barbell load increases (and thus system mass), the change in velocity decreases (noting that velocity is zero at the beginning of the propulsion phase). However, across all loaded conditions, the decrease in average velocity was not proportional to the increase in system mass (13, 25, 34, and 44% vs. 25, 50, 75, and 100% respectively). Simply put, mass increases more than velocity decreases, therefore, momentum continues to increase. So, although it is tempting to hypothesize that jump training with barbell loads of 75% of BM should be advocated (acknowledging that this notion is yet to be tested), we must note that the maximal impulse achieved by this load is a consequence of increasing mass, which has come at the expense of movement velocity and time (in this example, an extended pushoff duration). Arguably, the sporting arena requires that changes in range of motion (or displacement) are performed at high velocities, within time-constrained motor skills, and thus this training prescription may not optimally transfer to performance. Perhaps, power has become such a popular variable to report as high values also depend on at least moderate velocities, thus conforming to the demands of sport; when only one value is captured, power can at least control for sport specificity, given that force and velocity exhibit an inverse relationship (as discussed in the subsequent section).

In summary, it is important to note that net impulse may be maximized by either increasing the magnitude of the net force applied, or the duration for which the application occurs (with the latter causing a decrease in velocity if ROM is not increased). For example, Figure 4A illustrates 2 force-time and velocity-time traces for a CMJ, completed by the same athlete. Of note, jump height and thus net impulse is the same in both trials, but the strategy used to achieve each is different. In one trial (black line), the braking net impulse was characterized by a larger force and shorter time (and is thus representative of a desirable performance outcome in sport), while in trial 2 (gray line), the opposite occurred (13). Conversely, work can be maximized by either increasing the net force or the displacement over which the application occurs, with power then maximized through the duration for which the application occurs. When referring to Figure 4B, the athlete (the same athlete who was discussed above) produced identical mechanical work but through a larger force and shorter propulsion displacement in trial 1 (black lines) versus trial 2 (gray lines). Given the time and ROM constraints of most sporting activities, choosing a strategy that increases impulse or work by virtue of an increase in time or displacement may not be most suitable (again we should note that this is an untested statement). Therefore, when assessing impulse, our focus would need to be on both how much force was produced and how long it took to apply it. Because we want to improve both variables in our athletes, reporting these in addition to impulse is far more informative. The same statement can be made for power, in that the underpinning force, displacement, and time components must be considered. Clearly, an athlete who takes too long to complete a particular movement (whether that be a training exercise of sporting action) lacks one of, or a combination of, strength, RFD (explosive strength), or technical ability. The force-time curve should positively change as these components are improved; thus, analyzing the actual force trace is advocated.

**POWER AND THE FORCE-VELOCITY CURVE**

The final curve to analyze is the force-velocity curve (Figure 5), which practitioners often use to identify training loads...
corresponding to maximal power output (and how this changes over time), as well determining adaptations to training centering on the ability to produce force at high and low velocities. The reader should note that for athlete testing and training purposes, the force and velocity relationships generally noted and reported within S&C (including herein) pertain to an analysis of the concentric (propulsive) portion of whole-body movements (such as jumps, squats, and weightlifting derivatives), as opposed to those based on force and fascicle shortening as reported in the seminal research (Wickiewicz et al., (20)) and Komi (10). Also, because we require our athletes to always be “explosive” when lifting, movement velocity (of the body or barbell) is an outcome of resistive load, in that light loads will enable fast velocities, whereas heavy loads will generate slow velocities. These differences also explain why in S&C we typically define a more linear relationship between force and velocity, rather than the parabolic curve illustrated in single muscle fibers (and equally why some prefer to refer to the curve as a load-velocity curve).

In fully explaining and using the force-velocity curve, we must first address the quantitative and perhaps more sport-focused definition of power ($P$), that is, force multiplied by velocity ($P = F \times v$), hence the force-velocity curve. Logic dictates, therefore, that an increase in either variable (i.e., $F$ or $v$) will increase power if the other variable remains constant. Figure 5 illustrates that high forces are produced at low velocities, whereas high velocities generate low forces; thus, an inverse relationship exists between them. Theoretically, the highest values for power are produced when an optimal compromise between them is reached (but is exercise, athlete, and measurement method dependent). Such understanding deems that the placement of a sport motor skill on the force-velocity curve will depend on the mass of the object to be moved, given sporting actions call for the movement to be executed as quickly as possible within a given range of motion. For example, a rugby union tackle requires larger forces relative to those required to pitch a baseball and are hence at opposite ends of the curve. Because most sports require a variety of motor skills that span the entire force-velocity curve (Figure 6), it is considered prudent to ensure that training programs adequately cover all points. This is achieved through manipulation of exercise modality and/or training load and is discussed further in part 2 of this two-part review.

When it comes to identifying power, some researchers have sought to identify the peak instantaneous power, as opposed to average power (which has been the focus so far); this, however, may be seen as academically interesting rather than practically relevant. For...
example, Mundy et al. (14) found that for
the loaded CMJ, the majority of between-
participant differences in peak power
were either smaller than the CV, or the
smallest worthwhile change. Also, of
note, this variable only represents a −1
ms period (if data collected at 1,000 Hz),
which only corresponds to −1% of the
propulsion phase. From a mechanistic
perspective, average power may be a bet-
ner proxy marker for performance. Unlike
peak instantaneous power, average
power is typically found at the same load
for all athletes; in the CMJ, this is typically
at body mass (18). As intraindividual var-
iation cannot explain the decreases
observed in average power as load in-
creases, Mundy et al. (14) explained it
at a system level using mechanical theory.
As external load increases, the mecha-
nical work (recall that work = force ×
displacement) required to jump the same
height must then also increase. Because
countermovement displacement is lim-
ited by human anatomy (when aiming
to optimally use the stretch-shortening
cycle), more force must be applied. How-
ever, we are progressively unable to com-
pensate for the decreases in average
velocity caused by additional loads (or
rather our inability to meet them, given
our capacity to generate force), which
presents itself as an increase in propulsion
phase duration. Therefore, the decreases
observed in power (recall that power =
work/time) may be explained by the
increased time required to perform
mechanical work, over an anatomically
constrained propulsion phase.

CONCLUSION AND PRACTICAL
APPLICATIONS
All metrics, i.e., power, RFD, and
impulse, can be used to effectively mon-
itor athlete progress and define training
windows. When impulse is used, how-
ever, it is also important to capture
changes in this metric with respect to
changes in force and time, and in all
cases, it is informative to include the
force-time and force-velocity curves.
From a sport performance perspective,
however, it is worth remembering that
the goal is generally to increase force (at
high and low velocities), while simulta-
nously reducing the duration over
which force is applied. When reporting
and assessing the ability of an athlete to
quickly produce force, we advise practi-
tioners and researchers to consider sim-
ply identifying force at specific time
points (e.g., 0.1–0.3 seconds). This is
because if force at a specific time-point
increases, then impulse and RFD across
the same epoch must have also increased
(if body weight remains constant); fur-
thermore, this method limits error.
Finally, when reporting scientific find-
ings, it is important to forgo colloquial
terms for mechanical ones. However,
while coaching, telling an athlete you
want them to “explode” during

Figure 5. Theoretical illustration of the F-V relationship.

Figure 6. Theoretical placement of various sports motor skills on the force-velocity
curve. The placement of each motor skill is dependent on the mass of the
object to be moved because this will affect the force required to move it
and inversely affect the velocity it moves at.
a movement is acceptable because it appropriately infers the desired intent.

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Shyam Chavda is a strength and conditioning coach and technical tutor at the London Sport Institute, Middlesex University and the lead coach for the Middlesex University weightlifting club and a regional coach for British Weightlifting.

Paul Read is a strength and conditioning coach and clinical researcher at Aspetar Orthopaedic and Sports Medicine Hospital.

Peter Mundy is an assistant professor in biomechanics and course director in strength and conditioning at Coventry University.

Jason Lake is a reader in Sport and Exercise Biomechanics and program leader in MSc Strength and Conditioning in the Department of Sport and Exercise Science at the University of Chichester.

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