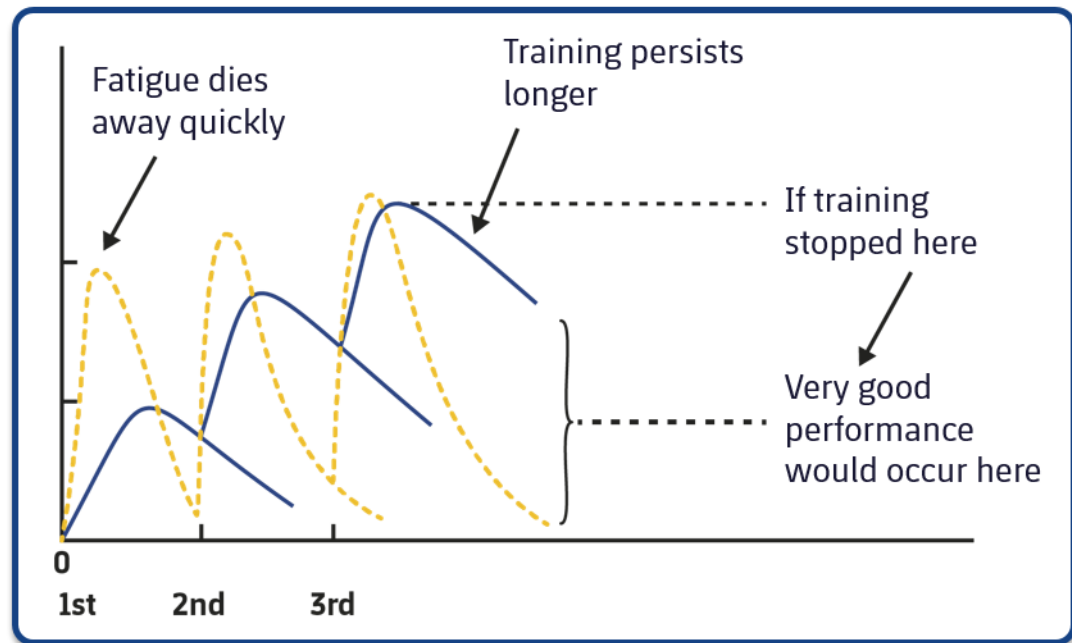


The Fitness and Fatigue Model

Let us take a look at the fitness and fatigue model. As we previously saw, Banister, Calvert, Savage and Bach (1975) first developed the fitness and fatigue model where it was proposed that performance was equal to the “fitness” developed in training minus the “fatigue” that was experienced because of training. Therefore, training is our input and then there are a number of factors that moderate this response (the output), e.g. physical qualities. There is the fatigue effect that arises from training, which typically comes and goes reasonably quickly. For example, this means that if we train on day 1 (e.g. Monday) and experience fatigue, we *will* likely need to recover on day 2 (e.g. Tuesday). Then, the athlete can go back and train again on day 3 (e.g. Wednesday). Fatigue is the negative effect of training, but there’s also a positive effect: fitness. This effect of training takes longer to build. Fitness builds over a long period and also dissipates relatively slowly. Therefore, performance (at least from a physical viewpoint), is equal to fitness minus fatigue. In Figure 1, we can see the graphic description of this phenomenon. Banister et al (1975) explain that the trained state is reached by the aggregation of separate impulses of training (TRIMPs) accumulated each day. As the figure shows, in the interval between training stimuli, the fitness state of the athlete decreases in a prescribed fashion, losing 2/3 of its initial value in a time constant. Succeeding training impulses then add to the training residue remaining from previous impulses. By joining the peaks of training impulses immediately after every training session, a growth curve of fitness may be traced with its own typical time constant. Similarly, fatigue grows in response to its phasic impulsive rise and logarithmic decay, driven by succeeding training impulses or fatiguing impulses. Fatigue impulses also build on the residual levels remaining after the decay of previous impulses, just like fitness grows (Banister, & Calvert, 1980).

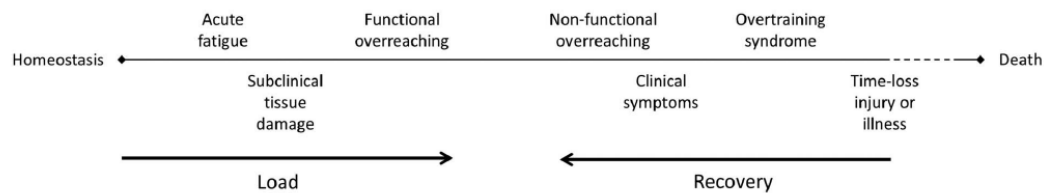
Figure 1: Fitness and fatigue responses to training stimuli



Source: Banister, & Calvert, 1980.

Before progressing further in the training load analysis, the International Olympic Committee (Soligard et al., 2016) expresses load and fatigue (depending on recovery) in the below figure:

Figure 2: The wellbeing continuum



Source: Soligard et al., 2016, as cited in Fry et al., 1991, p. 1032

Acute fatigue and functional overreaching is required in order for positive training adaptations to occur. However, if inadequate recovery is provided between training sessions, it may lead to non-functional overreaching or overtraining syndrome.

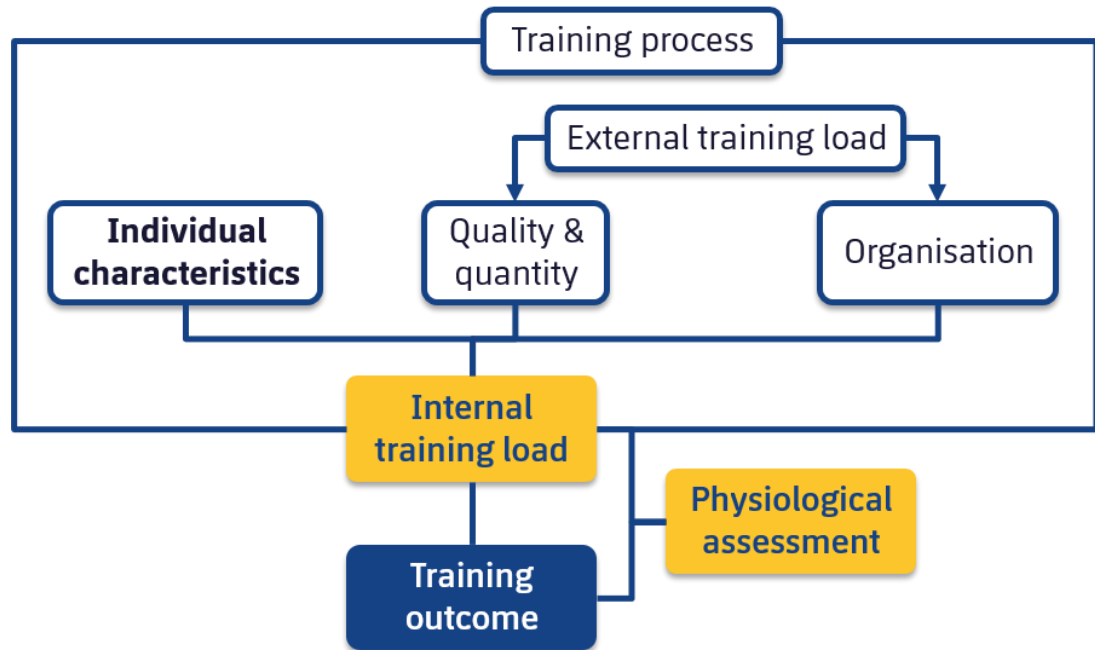
Training load monitoring

When load is quantified in training, we refer to two main points: external training load and internal training load. External load is the workload performed by the athlete, which encompasses the distance that he/she runs, the speed he/she runs, the tasks he/she is involved in during the practice. For example, a basketball player may wish to monitor the number of jumps that they make during the game; a weight lifter may collect the number of tons they lift. Essentially, it refers to the “work” that an athlete has performed. Internal load, on the other hand, is the physiological, psychological or biomechanical response to that external stimulus.

If training is considered as a process, it will be determined by the characteristics of physical exercises and tasks systematically repeated (external load). But if training is considered in terms of outcome (performance), it will be determined by functional, physiological and biomechanical expressions which will change because of training. Typically, internal load is measured through variables such as heart rate, blood lactate concentration or perceived effort (RPE scale). Training adaptation is governed by internal load; internal load is modified by manipulating external load. However, there are some factors that influence external load effects, such as genetic background and pre-training level (Impellizzeri, Rampinini, & Marcora, 2005).

Other factors influencing individual responses to load are stress, hours of sleep, age or training history. These factors, in isolation or combination, will determine the ability to tolerate workload and, therefore, the training outcome.

Figure 3: Training outcome as a consequence of training load



Source: modified from Impellizzeri et al., 2005.

It is important to consider that the same external load can provoke different internal loads in every person. For example, if two athletes with different physical status and qualities run the same distance at the same speed, both could finish with totally different heart rates and perceptions of effort, (and the performance of each will be different as well). Those two athletes may perform the same external workload, but the internal response to that workload will be quite different. An important point to keep in mind is that the external workload is the “work” an athlete completes, whereas the internal workload is the “response” to that work. Athletes have individual characteristics that allow them to tolerate different workloads and their ability to tolerate workload depends on a number of factors that are completely unrelated to training. It is the internal workload (individual response to each training task or competition) that drives adaptation. This means that we can moderate or adjust the internal training load, i.e. the internal response, through changes in the external workload. So, if the coach wants to create a higher internal load, a greater stress on the athlete in order to foster adaptation and, therefore, performance improvements, then he has to increase the external workload. Equally, if he/she wants to reduce the internal load, for a greater recovery, e.g. in order to minimize internal stress, reductions of external loads are required.

Some of the first attempts to estimate external load, at least in a team sport setting, were made by Professor Tom Reilly from Liverpool John Moores University. First, he devised a way to track athletes’ movements on a map of the

field in which he drew how far they ran, walked and sprinted. Afterwards, he progressed from the pen and paper method to an audio cassette recording himself every time someone changed direction or performed an activity on the football field. After the practice or the game, he would transcribe that information to determine the nature of work and rest ratios the athletes were performing. Of course, there was a large degree of error associated with this type of time-motion analysis, but it provides an appreciation of where player tracking began.

After audiocassette recording, video-based time motion analysis appeared, with up to ten individual cameras capturing the games and practices. There was one camera and its operator for each player. At the end of the game or training session, the coach would log the amount of time that players had spent standing, walking, jogging, striding and sprinting, as well as the number of times and the amount of time that athletes would spend passing the ball, dribbling, shooting and performing the various technical actions involved in the sport. For every ten minutes of game or training time, it took approximately 30 minutes to analyze a single player. Therefore, it took four and a half hours to analyze one individual player across a ninety-minute game! Around 2005, we used these techniques in women's football, generating data on the demands of international competitions and all training activities players performed to prepare for those competitions. This helped coaches understand the demands of international competitions as well as the type of training needed in order to prepare for those demands.

All this ended when training staffs started using GPS systems to track players and their performance. The analysis that once involved "describing events" turned into a much simpler one consisting of "numbers" obtained from GPS. This system allowed sport scientists to quantify the demands of competition for every training activity that players performed on the pitch, including multiple players at the same time. Even now, we no longer need coaches to download the data after the session, as we can obtain that information in real time. This actually allows coaches to interact with players and discuss real facts, showing them the kind of work rates that they were performing in training sessions. If they are above a certain load, then *some* sport scientists might reduce those loads; if they were not reaching the targets set for training, then they would be encouraged to train harder.

External load technology is always evolving. We initially had GPS technology sampling at 1 Hz, which means that one data point is obtained every second. But, for example, a particularly good player like Lionel Messi can change direction three times in one second. Since the sampling frequency is so low, the GPS would indicate that he is running in a straight line. So, one sample every second or a sampling frequency of 1 Hz wasn't enough for team sports and the accuracy was quite low. When the sampling frequency of GPS was increased to 5 Hz (five

samples every second), the accuracy and the reliability improved. And now there are GPS units that sample at 10 Hz (and even some reports of units on the market that sample up to 20 Hz), which is a very high sampling frequency. So GPS data is much more accurate, reliable and valid.

The addition of micro sensors (inertial measurement sensors) into GPS units has also changed the way we study training load. In addition to analyzing running or locomotor activities, such as high-speed running and sprinting, which are clearly important for many sports, the addition of micro sensors also allows sport scientists to monitor other game-specific activities. For example, the goalkeeper does not run long distances in a game and they do not perform a lot of sprinting or high-speed running. But they perform other activities in the game, which involve repetitive, high-intensity efforts: they have to accelerate really quickly, dive for a ball on the ground and then get back to their feet, and then maybe dive in another direction. GPS alone would indicate that the athlete had performed minimal work because they have essentially stayed in one spot. But when inertial measurement sensors are used, these devices can provide information on changes in direction, changes in body position (e.g. diving to the ground) and the time taken to get back to his feet. This is a kind of repetitive effort that is very specific to a football goalkeeper.

The gyroscope is another microsensor that provides information on the position of the body in space. Therefore, as the body rotates in space, this can be measured by the gyroscope. It's the same technology that we find in missiles or airplanes.

Accelerometers are also included in microsensor devices. They provide information on the accelerations that occur on the body within different planes. Some units have triaxial accelerometers, i.e. devices that work in three different planes: a vertical plane (up and down movements), forward and back movements and side-to-side movements.

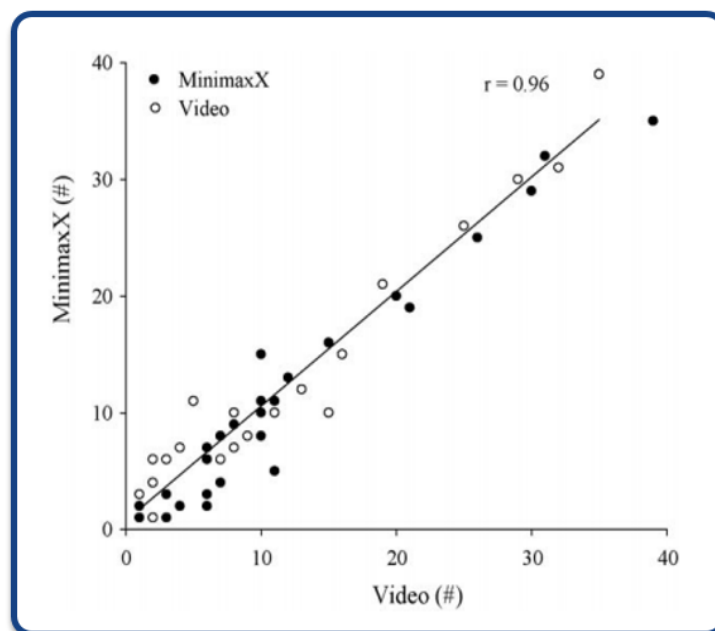
Finally, some units also contain magnetometers. A magnetometer is equivalent to an electronic compass. The first GPS units that were available for commercial use did not contain these electronic compasses: they would provide information on how much distance an athlete had run, but they would not provide information on the *direction* of that distance. That is, it was not possible to know if the athlete was moving forward or backwards or in a side-ways plane. The magnetometer provides this information. These three inertial sensors add considerably to wearable technology data and the understanding of external load. Below are some examples of how inertial sensors can be used in sports.

We have already seen how inertial sensors can be used in football (e.g. the football goalkeeper). Let us take an example from handball. Handball has some

throwing load that is not captured by GPS. Furthermore, GPS is not particularly useful for indoor sports, such as handball. In these types of sports, the accelerometers can quantify load (some companies called it “body load” or “player load”). With the combinations of additional sensors and algorithms, sport scientists can quantify the number of throws that someone makes in handball or baseball. Every throw made by a pitcher or an outfielder can be captured. We can also use accelerometers in skiing with winter programs using inertial sensors to capture aerial movements. In rugby, inertial sensors have been used to quantify tackles, rucks and scrums. There are now algorithms that are used in combination with inertial measurement sensors to capture when a scrum has actually occurred. This has really important practical applications. In a game there are analysts that code these scrums. We know when a scrum is occurring because they are shown on the television footage. However, in training, different positional groups will be involved in different activities. These devices provide an automatic scrum count. They automatically capture the scrums so analysts don’t actually have to manually count them.

Gabbett, Jenkins and Abernethy (2010) studied the effectiveness of using wearable technology compared to video analysis in order to measure the number of collisions experienced by professional rugby league players during training sessions. The correlation was 0.96 with no significant differences between the two methods.

Figure 4: Comparison of MinimaxX wearable technology and video methods for recording collisions



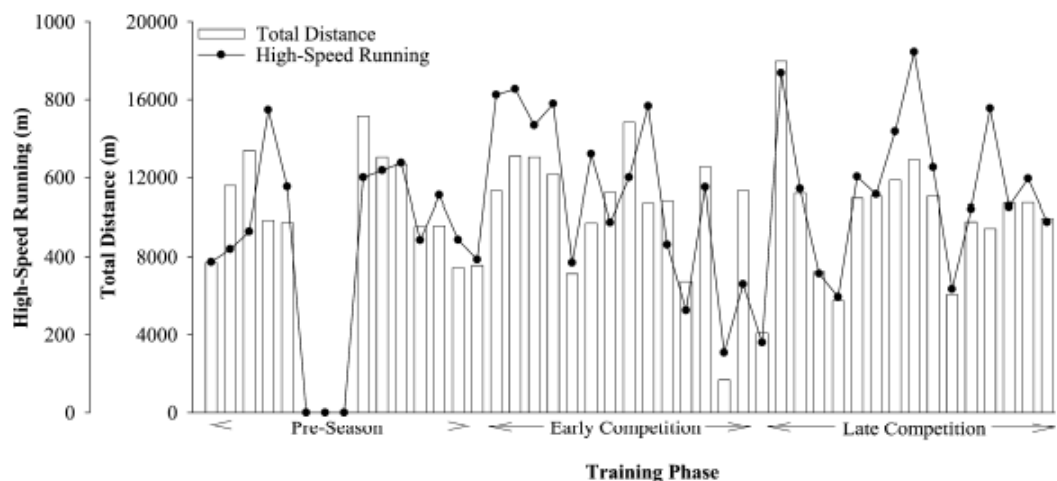
Source: Gabbett et al., 2010, p. 580.

Inertial measurement sensors can also be used in water sports. It has also been used in activities like swimming to quantify stroke rates and stroke counts. As we have seen, there are a number of practical applications of inertial measurement units that add value to the GPS data obtained in sport.

Figure 4 shows external load, measured by GPS technology and accelerometers, and how it can change over the course of a season. This figure shows the relationship between the total distance covered and the high speed running during the different periods of a full season. For this particular playing group, in the pre-season, there was a large total distance covered with a small amount of high-speed running distance. On the other hand, later in the competitive phase of the session, this relationship was reversed and the amount of total distance covered decreased and the high-speed running distance increased. This particular training program could potentially result in players being underprepared for the high-speed running demands of competition.

Figure 5 shows the relationship between different external workloads (measured in movement speed and types of movements such as repeated high intensity effort bouts) and injury risk. Both figures correspond to the same professional rugby league team.

Figure 5: Total distance covered vs. high speed running distance



Source: Gabbett, & Ullah, 2012, p. 956

Figure 6: Potential risk factors for soft-tissue training injuries in professional rugby league players

Risk factors		Injury incidence (95% CI)		
		Transient	Time loss	Missed matches
Injury history in the previous season	No	36.7 (21.7–57.9)	42.8 (26.5–65.4)	12.2 (4.5–26.6)
	Yes	38.1 (23.9–57.6)	45.0 (29.4–65.9)	13.8 (6.0–27.3)
Total distance	≤3,910 m	57.4 (36.0–87.0)	67.9 (44.3–99.5)	18.3 (7.3–37.0)
	>3,910 m	26.2 (15.6–41.5)	30.6 (19.0–46.8)	10.2 (4.1–21.0)
Relative distance	≤60 m·min ⁻¹	36.4 (22.8–55.0)	44.6 (29.4–64.9)	13.2 (5.7–26.1)
	>60 m·min ⁻¹	39.1 (23.2–61.8)	43.5 (26.6–67.1)	13.0 (4.8–28.3)
Very-low intensity	≤542 m	57.5 (36.0–87.0)	65.3 (42.3–96.4)	18.3 (7.4–37.7)
	>542 m	26.5 (15.7–41.9)	32.4 (20.3–49.1)	10.3 (4.1–21.2)
Low intensity	≤2,342 m	57.6 (36.1–87.2)	70.7 (46.6–102.9)‡	18.3 (7.4–37.8)
	>2,342 m	26.5 (15.7–41.9)	29.5 (18.0–45.5)	10.3 (4.1–21.3)
Moderate intensity	≤782 m	60.8 (39.7–89.1)‡	63.1 (41.6–91.9)	23.4 (11.2–43.0)
	>782 m	22.1 (12.1–37.1)	31.5 (19.3–48.7)	6.3 (1.7–16.2)
High intensity	≤175 m	42.2 (26.1–64.5)	48.2 (30.9–71.8)	14.1 (5.7–29.0)
	>175 m	33.7 (20.3–52.6)	40.8 (25.8–61.2)	12.4 (5.0–25.6)
Very-high intensity	≤9 m	31.2 (18.2–50.0)	47.8 (31.2–70.0)	12.9 (5.2–26.5)
	>9 m	44.5 (28.2–66.7)	40.6 (25.1–62.1)	13.5 (5.4–27.9)
Total high intensity	≤190 m	39.1 (23.9–60.4)	43.0 (27.0–65.1)	13.7 (5.5–28.1)
	>190 m	35.9 (21.9–55.4)	44.9 (29.0–66.2)	12.6 (5.0–25.9)
Mild acceleration	≤186 m	70.4 (47.1–101.1)‡	67.9 (45.1–98.2)‡	17.0 (6.8–35.0)
	>186 m	16.9 (8.5–30.3)	29.3 (17.6–45.7)	10.8 (4.3–22.2)
Moderate acceleration	≤217 m	65.3 (43.0–95.0)‡	70.1 (47.0–100.7)‡	16.9 (6.8–34.9)
	>217 m	20.1 (10.7–34.3)	27.8 (16.5–43.9)	10.8 (4.3–22.2)
Maximum acceleration	≤143 m	61.6 (39.9–91.0)‡	69.0 (45.9–99.7)‡	14.8 (5.4–32.2)
	>143 m	22.9 (12.8–37.8)	29.0 (17.5–45.3)	12.2 (5.3–24.1)
Repeated high-intensity effort bouts (no.)	≤3	46.3 (26.5–75.2)	46.3 (26.5–75.2)	14.5 (4.7–33.8)
	>3	35.5 (20.3–57.6)	55.4 (35.9–81.8)	11.1 (3.6–25.9)

*CI = confidence interval.

†All injuries were classified as a transient (no training missed), time loss (any injury resulting in missed training), or a missed match (any injury resulting in a subsequent missed match) injury. Rates are reported per 1,000 training hours (and 95% CI).

‡p < 0.01.

Source: Gabbett, & Ullah, 2012, p. 957

Now that external load has been discussed, let's turn our attention to internal load. Heart rate can be easily measured using heart rate straps to obtain this data in real time. Blood lactate concentration (as a measure of the intensity of an athlete's activity) can be obtained with a simple finger prick or an ear sample. But how can we monitor the intensity of training sessions or competition with minimal resources? The rating of perceived exertion (RPE) provides an inexpensive method of quantifying internal load in these situations. Gunner Borg provided much of the early research on the RPE scale. He examined factors that influenced a subject's perceived exertion, such as physical or psychological activities. His scale has been used in multiple studies around the world. One of the first scales was the 6-20 scale which roughly corresponded with heart rates that would occur between 60 and 200 beats per minute. On this scale, a value of six was the easiest activity that an athlete would ever do and 20 was the hardest activity an athlete would ever complete. Since the early studies of Borg, several authors have modified the RPE scale with Carl Foster performing a large amount of work in this area. Sweet, Foster, McGuigan, & Brice, (2004), used the session RPE and modified it slightly to use some more athlete specific or "athlete friendly"

descriptors. They also changed the numbers involved in this scale. So, rather than using the 6-20 scale they used the 0-10 scale, where zero was rest and ten was the maximum exercise intensity that an athlete had ever performed.

Figure 7: Modifications of the category ratio rating of RPE scale

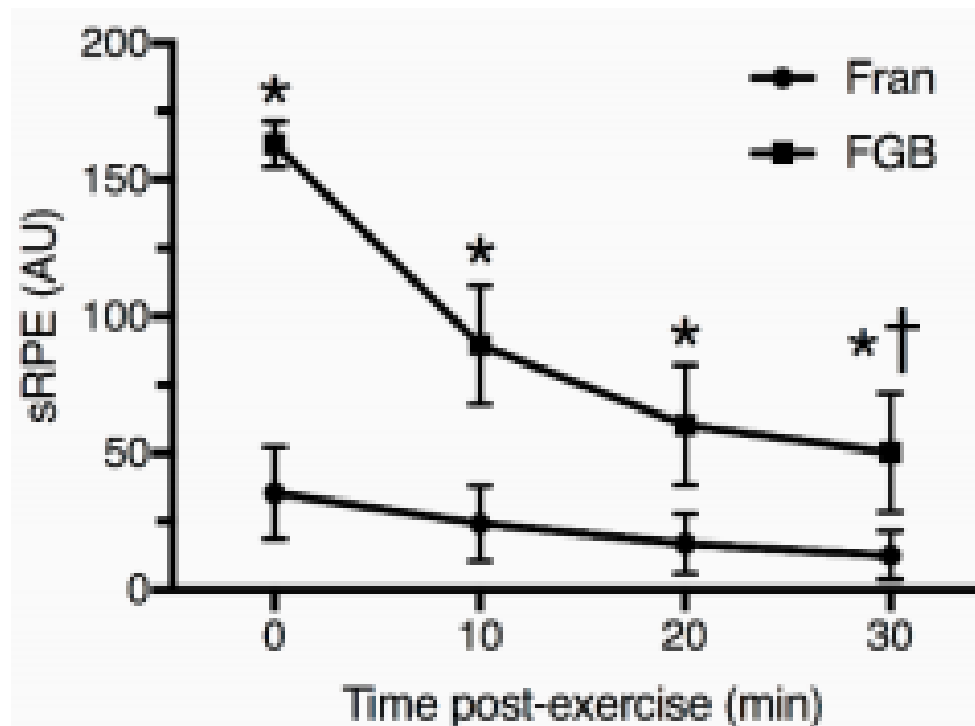
Rating	Descriptor *
0	Rest
1	Very, very easy
2	Easy
3	Moderate
4	Somewhat hard
5	Hard
6	-
7	Very hard
8	-
9	-
10	Maximal

Source: Sweet, Foster, McGuigan, & Brice, 2004, p.797

Foster used the session-RPE in a practical way by asking athletes to rate the intensity of their completed session. Athletes were asked a simple question “how hard was your session?” When he initially developed and trialed this scale, Foster used a 30-minute delay before obtaining the RPE response. The reason for using a 30-minute delay is that athletes tend to remember the last activity they performed in a session and therefore rate the overall intensity based on that final activity. If a training session was relatively easy (for the most part), but the last ten minutes of it was really hard, athletes, tended to remember the last part of the session, and would therefore rate that the whole session was really hard. Equally, athletes tended to do the reverse as well: if they started the session very hard, and then finished with some light training activities, they tended to remember that and they would rate that the session much easier than what it actually was. This is why we encourage the 30-minute delay following the completion of the training session or the match to obtain the RPE measure. There are some studies that have shown no difference in timing: the same result is obtained with a 30-minute delay or without it. But in other activities, (e.g.

Crossfit), there is work that has shown that the longer athletes wait to give the RPE score, the lower the RPE tends to be (Tibana, de Sousa, Cunha, Prestes, Fett, Gabbett and Voltarelli 2018).

Figure 8: Session rating of perceived exertion (sRPE) at different post-exercise times after two different workout protocols.



Source: Tibana, de Sousa, Cunha, Prestes, Fett, Gabbett and Voltarelli (2018)

RPE is considered a valid and reliable method of estimating internal load. In the past module we discussed the strong associations between RPE and heart rate ($r = 0.89$) and blood lactate concentration ($r = 0.86$). Foster et al. (2001), compared session-RPE and heart rate during steady state and high-intensity exercise. They used the summated heart rate method, where 5 zones based on Heart Rate peak percentages were calculated: (1) 50-60%, (2) 60-70%, (3) 70-80%, (4) 80-90%, (5) 90-100%. The activities evaluated in this study resulted in the values shown in figure 7:

Figure 9: Summated HR zones vs. session RPE

	Summated HR zone	Session RPE
30 min steady state	110 ± 24	130 ± 57*
60 min steady state	216 ± 39	270 ± 63*
90 min steady state	350 ± 44	432 ± 67*
30 s/30 s interval	107 ± 14	131 ± 45*
60 s/60 s interval	117 ± 18	148 ± 54*
120 s/120 s interval	114 ± 17	146 ± 47*
+10% interval	114 ± 16	136 ± 60*
+25% interval	117 ± 18	148 ± 54*
+50% interval	114 ± 111	161 ± 46*
Basketball	652 ± 59	744 ± 84*

Source: Foster et al., 2001, p. 113.

They concluded that this data provided support for the use of the session RPE method as a subjective estimate of training load during non-steady state exercise, including very high-intensity interval training and team sport practice and competition.

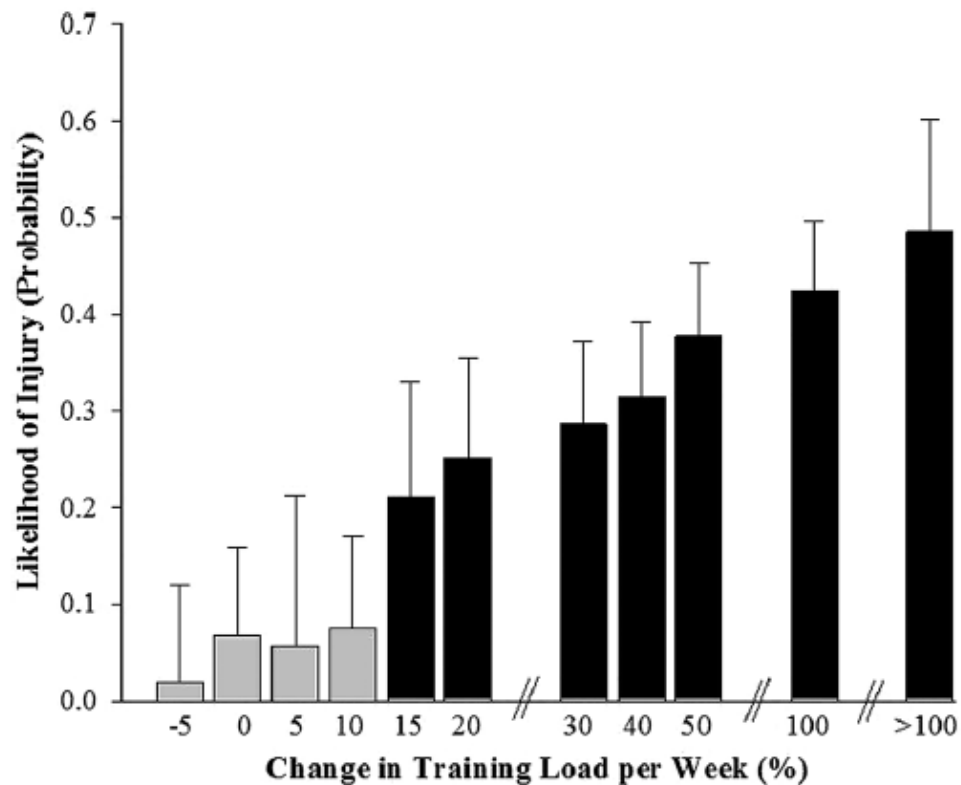
The RPE provided immediately after a training session tends to be higher than that given after a 30-minute lapse. Training load is a function of frequency, volume, and intensity. Along with the intensity provided by RPE, “volume” (measured by training duration) is also required in order to estimate training load. When calculating internal training load the session RPE is multiplied by the duration of the session (in minutes).

For example, if an athlete indicates that a training session was “hard”, this would equate to a rating of 5 on the RPE scale. As an example, for a sixty-minute session, the RPE is multiplied by the duration to provide training load. So, 5 x 60 would give 300 training load units or 300 workload units.

With this information, we can also calculate the training monotony. The training monotony is a really important variable because it provides an indication of the variation within the training. If an athlete has no variation in their training, and they are either training at constantly high loads or constantly low loads; i.e. there is no fluctuation in loads, this indicates that they are either getting insufficient

recovery or inadequate training stimulus. Either way, when the variation is low, training monotony will be high. To calculate monotony, the average load for the week is divided by the standard deviation of the load for the week. If training monotony is high, an athlete's injury risk will also be high. Although high training monotony may increase the risk of injury, large changes in weekly training load also carry a high injury risk. Piggott et al (2009) demonstrated that increasing training loads by more than 10% from week to week was responsible for 40% of injuries sustained by Australian football players. Also large (>2 standard deviation) changes in internal load (more than 1069 arbitrary units from one week to another) increased risk of injury in rugby union players. Gabbett (2016) modeled the relationship between changes in weekly training load and injury risk in professional rugby league players (Figure 8).

Figure 10: Changes in week-to-week training load vs. likelihood of injury



Source: Gabbett, 2016, p.5

The final calculation that can be made from training load information is a variable called "training strain". Training strain is the product of weekly load and training monotony.

Figure 11: Formulae for load, monotony and strain

$$\text{RPE} \times \text{duration (min)} = \textbf{Load}$$

$$\text{Mean load/SD load} = \textbf{Monotony}$$

$$\text{Weekly load} \times \text{monotony} = \textbf{Strain}$$

Source: prepared by the author.

Take the training load for the week and multiplying this value by the training monotony, will provide the training strain. Training strain is an important variable. Having high loads is not necessarily a bad thing: if high loads are built in the correct manner then injury risk may actually be lower. However, if an athlete has high training loads with low variation, (i.e. with high training monotony), this may lead to high training strain. As shown from the early research of Foster, high training monotony and training strain is associated with increased risk of injury and illness.

In summary, this section has discussed Banister's "fitness-fatigue" model (i.e. performance is equal to fitness minus fatigue). When an athlete's fitness is high and their fatigue is low, then they are physically prepared to perform well. But when fatigue is high and fitness is low, the athlete is at risk of injury and potentially poor performance. Finally, external and internal load has been discussed, including the wide range of methods used to quantify relevant external load for different sports, and the different options available to quantify internal load. It is the combination of external and internal loads that provides our training outcome.

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