Content

1 Introduction

Vertical jumps are a popular way for coaches and sport scientists to assess performance of the lower body neuromuscular functions of athletes and are frequently used to monitor fatigue and recovery responses in a variety of sports.[1] Laboratory equipment, such as force plates and jump mats, are often required to perform vertical jump analysis. However, equipment such as mentioned above are expensive, and visits to a laboratory are time-consuming. Therefore, an easy, inexpensive way to perform and interpret jump tests is needed for daily training readiness assessment and for training monitoring with the aim to prevent overtraining, reduce injuries, monitor the effectiveness of training programs, and ensure consistence of performance throughout competitive periods.

The rationale for optimal training is simple: Heaviest exercises should be timed at the peaks of performance, whereas low intensity training is the best option when performance is at its lowest. The problem is how to identify those highs and lows. One can obviously rely on subjective feeling, but this can be deceiving when the recovery period exceeds a few days. For example, after a frequently occurring bout of activity, such as a football match, reduction in jump height is small to moderate, equating to about 5% and recovery takes 72 hours.[2,3] After an unusual task, such as a 90 km foot race, reduction in jump height can be as high as 20% and it may take 10–20 days before recovery is completed (Figure 1).[4] Thus, quantitative methods such as a jump test may assist in knowing when it's time to train hard and when to take it easy. And what could be easier than having this ability in your wrist device.

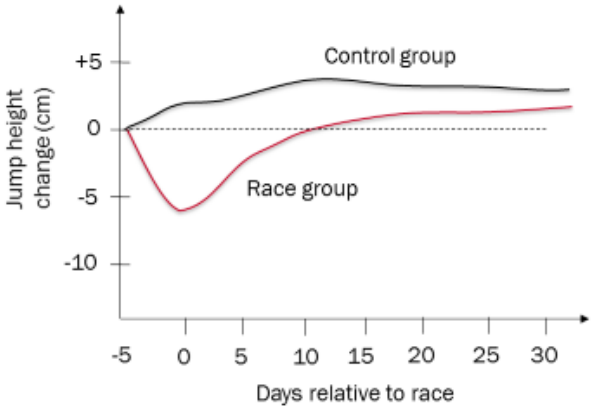

Figure 1. Example of jump height recovery after 90 km foot-race.[4]

2 Physiological background

The main output parameter from a vertical jump test is jump height. To achieve great jump height, the jumper must obtain high take-off velocity. Just like a spaceship carrying a satellite must achieve high horizontal velocity to reach the earth's orbit. A jumper can't get to the orbit, but tries to achieve a high vertical take-off velocity to stay in the air for as long as possible. As squat depth limits the distance that is available to supply power, muscles need to supply power as fast as possible during the push-off phase. Consequently, vertical jump test is an easy way to assess the legs' "explosive" power. In addition, as vertical jump height also correlates with maximal strength and horizontal acceleration,[5] even athletes who do not regularly jump will benefit from jump test.

2.1 Leg recovery test

Jump test is a powerful tool to quantify neuromuscular recovery state. We have highlighted this by naming the jump test as **Leg recovery test** in Polar ecosystem. Leg recovery test also interacts with other features, such as Cardio recovery, to yield universal training readiness guidance without the need for expensive

equipment or a laboratory test. More about Leg recovery test interpretation can be found in the later sections of this paper.

Following the recovery state is important because injury risk may increase if neuromuscular function is impaired, especially during speed and strength training. Speed and strength training are essential for improving performance in most sports, and assist in gaining capabilities relevant for well-being. Thus, assessing the recovery state of the neuromuscular function is critical for safe training targeted to improve sports performance and/or quality of life.

2.2 Jump technique

Vertical jump tests can be performed with a variety of different techniques. Here we focus on the most popular version that we also use in recovery assessment: the countermovement jump (CMJ) test. When performing a CMJ test, it's crucial to pay attention to technique to obtain reliable results.

Prepare for the jump by placing hands firmly on your hips and standing straight. Squat quickly and jump as high as you can by supplying power equally from both legs. Don't bend your knees in the air before touchdown. After touchdown, knees can be bent to allow smooth landing. Hands must be kept on hips throughout the movement for two reasons: 1) It prevents using upper body muscles to power movement; and 2) The sensor estimates the body's trajectory from the wrist, and therefore it's important to keep the wrist close to jumper's center of mass.

3 Technological background

The conventional method to obtain vertical jump height is a jump mat, which is a device that measures flight time utilizing a mechanical or optical switch. Although jump mats are small enough to fit into a shoulder bag, they are not portable in any modern-day standards. Therefore, inventors have recently started to pay attention to small motion tracking sensor called inertial measurement units (IMU). Due to their lightweight size, IMU's can be placed inside a sports watch and consequently assist in jump height assessment. Determination of jump height with IMU is not a trivial task though, as can been seen in Table 1.

Table 1. Literature summary of IMU-derived jump test validity.

Reference	ICC	Bias (cm)	95% CI (cm)
Casartelli 2010[6]	0.98	7.2	2.8
Rantalainen 2018a[7]	0.89	5.5	3.4
Rantalainen 2018b[8]	0.96	4.3	3.2
Picerno 2011[9]	0.83	0.6	5.4
Lesinski 2016[10]	0.86	0.6	3.3

ICC = intra-class correlation coefficient; CI = confidence interval

4 Validation

We assessed jump test concurrent validity and test-retest reliability by comparing IMU-derived jump height against a criterion measure, which was a jump mat (Powertimer, Newtest, Oulu, Finland). A total of 20 participants were recruited in-house to repeat CMJ tests on four different days. Results were produced with the final algorithm, but the device we used was a prototype. We will update validation results with the production model to this document as soon as they are available.

IMU's validity was assessed with correlation coefficient, mean bias and 95% confidence interval. Results show that there is a strong correlation between the jumps heights from the jump mat and IMU ($r = 0.85$) and mean jump height from IMU (31.5 cm) was slightly less than the jump height from the jump mat (31.8 cm). Test-retest reliability was assessed with coefficient of variation (CV). The slight edge that the jump mat (CV = 4.8%) had over IMU (CV = 6.2%; smaller is better) is in practice likely to be compensated by integration of the IMU to a smartwatch, which will result in much more jumps eventually being recorded with the smartwatch than with a jump mat.

Table 2. Comparison of IMU and jump mat. Concurrent validity was reported with Pearson's correlation coefficient (CC), mean bias and 95% confidence interval (CI). Test-retest reliability reported with coefficient of variation (CV).

CC	Bias (cm)	95% CI (cm)	CV (%)
0.85	-0.3 cm	5.6 cm	6.2

5 Advantages

Benefits of the Leg recovery test are:

- gives valuable training guidance
- always available
- does not require an additional sensor
- easy to learn even for a beginner
- no fitness prerequisites
- recovery feedback without any prior knowledge of training
- interacts with other tests and provides individual training readiness guidance based on several physiological measurements
- tracks the development of the explosive power in the legs

6 How to interpret results

Leg recovery test measures jump height and its interpretation is given by comparing today's result to a 28-day rolling average (baseline). This approach has been chosen because performance varies substantially between individuals, it is important to delimit thresholds for unusual changes using individual data.[12] Interpretation is called **Leg recovery status** and it will be given as *recovered* or *not recovered*. Leg recovery status follows the given rule:

- If baseline equates to at least 28 cm, and the current result is 7% or more below the baseline, Leg recovery status is not recovered.
- If baseline equates to under 28 cm and the current test result is 2 cm or more below the baseline, Leg recovery status is not recovered.
- In all other cases, Leg recovery status is recovered.

With this definition, the likelihood that the user gets a negative Leg recovery status simply because of normal daily variation is very low and it is also in line with the recommendation by Taylor et al.[12]

Each Leg recovery test comprises of three CMJ's. To deal with unrealistically high or low jump heights that may occasionally occur, Leg recovery test calculates difference between the highest and the lowest jump and if this exceeds 10 cm, jump height is given as median of the three jumps, otherwise as mean. Why not simply use the best jump? Because, a meta-analysis has shown that calculating an average is better than taking the maximum value in tracking the neuromuscular status.[11]

To ensure the reliability and repeatability as well as technological accuracy of the jump test, it is very important to follow given instructions considering test procedure.

6.1 Readiness for speed and strength training

Leg recovery status assesses the recovery of the neuromuscular system, as opposed to Cardio recovery status which assesses the recovery of the cardiovascular system. As the neuromuscular system is mainly strained in speed and strength training, Leg recovery status reflects readiness for speed and strength training.

Types of activities that fall into the speed and strength training category include gym, sprint running, most team games, or anything that contains short bursts of intense activity. As a rule of a thumb, in neuromuscular training, your heart rate rarely exceeds zones 1–3 (unless you're a very experienced athlete), because heart rate responds with a delay to an increase in intensity. If your watch features Polar Running power measurement, neuromuscular training should take you to briefly visit zones 4 and 5, provided that your zones are set correctly.

In comparison, Leg recovery test is not the best indicator of your readiness for endurance training that stresses your cardiovascular system. Consequently, even if your Leg recovery status is compromised, we may recommend walking, hiking, swimming, cycling or even running depending on the other test results. Endurance training equates to zones 1–3 in Running power scale.

Speed and strength training requires maximal neural drive to muscles and full power supply from the muscles. If vertical jump height is lower than usual, maximal neural drive to muscles may be temporarily

lost, or muscle performance diminished by local muscle glycogen depletion[13,] or there may be muscle damage. Consequently, speed and strength training should be avoided on days when Leg recovery status is Not recovered. As the name of the test implies, Leg recovery test captures the readiness of your legs, not core, shoulders or arms. Thus, your upper body may or may not be ready for speed and strength training when Leg recovery status is negative.

7 Limitations

There is an obvious technical limitation to the jump test that is related to positioning of the sensor. It's assumed that the device captures the motion of the centre of mass. This is problematic if the user moves their hands during a jump. Even if the hands are kept tightly at the hips – as instructed – there aren't two identical jumpers when it comes to arm movement. As a result, we do not recommend that you compare jump heights with a friend. Jump test is best used as your personal readiness guide.

Another limitation is human physiology that is too complex to be decoded by single test result. Jump test assesses neuromuscular fatigue but cannot differentiate between upper and lower body. In addition, the test cannot tell the difference between fatigue mechanisms. Therefore, it cannot advise on the best strategy for fastest recovery. In a nutshell, when neuromuscular fatigue is caused by neural factors or muscle damage, which you may identify from muscle soreness 1–2 days after exercise, the best strategy is usually just to rest and wait for the muscles to heal themselves. When fatigue is caused by long-lasting exercise and consequent local muscle energy depletion, you may be well-advised to consume plenty of carbohydrate rich food after the exercise to replenish your energy resources sooner.

8 References

1 Taylor, K., Chapman, D. W., Cronin, J. B., Newton, M. J., Gill N. (2012). Fatigue monitoring in high performance sport: A survey of current trends. Journal of Australian Strength and Conditioning, 20 (1), 12–23

2 Duffield, R., A. Murphy, A. Snape, and G. M. Minett, Skein, M. (2012). Post-Match Changes in Neuromuscular Function and the Relationship to Match Demands in Amateur Rugby League Matches. Journal of Science and Medicine in Sports, 15, 238–42

3 Silva, J. R., M. C. Rumpf, M. Hertzog, C. Castagna, A. Farooq, O. Girard, and K. Hader. (2018). Acute and Residual Soccer Match-Related Fatigue: A Systematic Review and Meta-Analysis. Sports Medicine, 48 (3), 539–83

4 Chambers, C., T. D. Noakes, E. V. Lambert, and M. I. Lambert. (1998). Time Course of Recovery of Vertical Jump Height and Heart Rate versus Running Speed after a 90-Km Foot Race. Journal of Sports Sciences, 16 (7), 645–51

5 Wisløff, U., C. Castagna, J. Helgerud, R. Jones, and J. Hoff. (2004). Strong Correlation of Maximal Squat Strength with Sprint Performance and Vertical Jump Height in Elite Soccer Players. British Journal of Sports Medicine, 38 (3), 285–88

6 Casartelli, N., Müller, R. and Maffiuletti, N. A. (2010). Validity and Reliability of the Myotest Accelerometric System for the Assessment of Vertical Jump Height. Journal of Strength and Conditioning Research, 24 (11), 3186–93

7 Rantalainen, T., Hesketh, K. D., Rodda C. & Duckham, R. L. (2018). Validity of Hip-worn Inertial Measurement Unit Compared to Jump Mat for Jump Height Measurement in Adolescents. Scandinavian Journal of Medicine and Science in Sports, 28 (10), 2183-2188

8 Rantalainen, T., Gastin, P. B., Spangler, R. & Wundersitz, R. (2018). Concurrent Validity and Reliability of Torso-Worn Inertial Measurement Unit for Jump Power and Height Estimation. Journal of Sports Sciences, 36 (17), 1937–42

9 Picerno, P., Camomilla, V. & Capranica, L. (2011). Countermovement Jump Performance Assessment Using a Wearable 3D Inertial Measurement Unit. Journal of Sports Sciences, 29 (2), 139–46.

10 Lesinski, M., Muehlbauer, T. & Granacher, U. (2016). Concurrent Validity of the Gyko Inertial Sensor System for the Assessment of Vertical Jump Height in Female Sub-Elite Youth Soccer Players. BMC Sports Science, Medicine and Rehabilitation, 8, 35.

11 Claudino, J. et al. (2016). The countermovement jump to monitor neuromuscular status: A meta-analysis. Journal of Science and Medicine in Sport, 20 (4), 397–402

12 Taylor, K. L., Hopkins, W. G., Chapman, D. W., Cronin, J. B. (2016). The influence of training phase on error of measurement in jump performance. International Journal of Sports Physiological Performance, 11 (2), 235–9

13 Krustrup, P. et al. (2011). Maximal Voluntary Contraction Force, SR Function and Glycogen Resynthesis during the First 72 H after a High-Level Competitive Soccer Game. European Journal of Applied Physiology, 111 (12), 2987–95.