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The reliability and validity of different jump-test performance metrics for fatigue monitoring in amateur boxing

Callum Blades[1, 2 *], Mick Wilkinson[2]

[1]Department of Sport, Exercise and Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, UK
[2]School of Sport, Faculty of Education, Health and Wellbeing, University of Wolverhampton, UK

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ABSTRACT
Jump testing has become widespread practice in sport science for monitoring athletes' fatigue. The purposes of this study were to determine whether the number of trials performed influenced the reliability of jump-test performance metrics, as well as establish the construct validity of these jump-test performance metrics for monitoring fatigue in amateur boxing. After institutional ethical approval, seven novice (stature 1.81 ± 0.08 m, mass 82.7 ± 12.4 kg, age 20.9 ± 0.8 years, training <6 months) and seven experienced amateur boxers (stature 1.74 ± 0.12 m, mass 71.3 ± 13.5 kg, age 22.0 ± 3.4 years, training >18 months) participated. All boxers completed familiarisation and three experimental trials, involving a standardised warmup and eight jump-tests. These jump-tests included countermovement and squat jumps, performed bilaterally and unilaterally as well as vertically and horizontally. For each jump-test, 12 performance metrics were calculated using the maximum, mean or median height or distance, from combinations of the four attempts performed per jump-test, with and without one initial practice. Trial two also involved 3 x 2 min rounds of sparring to induce fatigue. Reliability was calculated for novice and experienced boxers separately using typical error between trials one and two, which ranged from 1.5 to 19 cm across the performance metrics. Construct validity was determined by a 2 x 2 within and between group ANOVA (novice v experienced, trial two v three). Only unilateral vertical squat jump height could discriminate experienced from novice boxers after a fatiguing sparring bout. Jump height of experienced boxers was lower than novices by 2.0 ± 0.2 cm (p = 0.01, 95% CI [1.1, 3.0] cm) when using the mean of two attempts after one practice. As typical error was 1.3 cm, results suggest that this jump-test and performance metric appear reliable and valid for monitoring fatigue in amateur boxing.

1. Introduction

Fatigue monitoring is widespread in sport science to avoid the development of non-functional overreaching, track long term improvements over time and inform training program periodisation (Halson, 2014). Amateur boxing is a high intensity intermittent sport where boxers perform 2-3 min rounds of exercise at a blood lactate averaging 13.5 ± 2 mmol/L, interspersed with 1 min rest periods of insufficient duration to enable complete recovery (Delvecchio, 2011). These rounds are performed during training, via sparring, as well as within competitive bouts, meaning that boxers accumulate substantial levels of neuromuscular fatigue from generating upwards of 2,643 N of force per punch (Delvecchio, 2011). The reduction in body mass that occurs before competitive bouts is also associated with a significant decline in neuromuscular system performance (Zubac et al., 2020). Consequently, it is necessary to identify effective monitoring batteries that are specific to the detection of neuromuscular fatigue in amateur boxing.

Effective fatigue monitoring batteries require reliable and valid tests (Pyne et al., 2014). A reliable test produces consistent results under standardised conditions (Ortega et al., 2008), while

*Corresponding Author: Callum Blades, School of Sport, Faculty of Education, Health and Wellbeing, University of Wolverhampton, UK, C.Blades@wlv.ac.uk

a valid test will correctly measure the concept of interest (Castro-Piñero et al., 2010). Although reliability is determined using test-retest protocols (Ortega et al., 2008), validity can be confirmed through either criterion or construct approaches (Castro-Piñero et al., 2010). Criterion validity is the extent to which a test correlates with a gold standard, while construct validity is the extent to which a test discriminates ability or predicts performance (Castro-Piñero et al., 2010). As there is no accepted gold standard test of fatigue (Lambert & Borresen, 2010), construct validity must be used alongside test-retest reliability to confirm the effectiveness of tests within an amateur boxing fatigue monitoring battery.

Jump tests are currently a popular field-based measure used in fatigue monitoring batteries (Taylor et al., 2012). The most common jump tests include countermovement jump (CMJ), squat jump (SJ) and horizontal jump, with all three possessing good levels of test-retest reliability (Markovic et al., 2004; Moir et al., 2009; Thomas et al., 2017). While a meta-analysis also infers strong construct validity of the CMJ for monitoring fatigue (Claudino et al., 2017), the validity of both the SJ and horizontal jump are less clear. While research confirms SJ height and soccer players training load were positively related throughout a season (Sams et al., 2018), it remains disputed as to whether SJ height provides greater reliability and validity to CMJ height for fatigue monitoring (Gathercole et al., 2015). The validity and reliability of all jump tests are further confounded by different metrics being calculated in the literature, with studies using the maximum height from two recorded jumps (Oliver et al., 2015), the maximum height from three recorded jumps (Wiewelhove et al., 2017), the mean height from three recorded jumps (Maulder & Cronin, 2005) and the maximum height from three recorded jumps after two practices (Thorpe et al., 2015). Consequently, further investigation is necessary to establish whether the validity and reliability of each jump test is affected by the number of recorded and practice attempts being used to calculate the metric of jump performance.

In addition to validity and reliability, the specificity of a test to the sport remains an important, but often overlooked, requirement of an effective test (Reilly et al., 2009). Considering this, a key physiological determinant of amateur boxing is the expression of unilateral lower body force horizontally (Chaabène et al., 2015). Despite this, mainly bilateral and vertical jumps have been investigated within the literature for fatigue monitoring (Maulder & Cronin, 2005; Oliver et al., 2015; Thorpe et al., 2015; Wiewelhove et al., 2017). Theoretically, horizontal and unilateral jumps should be more specific to amateur boxing, but this requires investigation in the context of fatigue monitoring. Therefore, the aim of this study was to examine the test-retest reliability and construct validity of various metrics of jump-test performance for fatigue monitoring in amateur boxing.

2. Methods

2.1. Design

A repeated measures parallel group design was used, with two groups comprising either novice or experienced amateur boxers. Each group completed one familiarisation trial and three experimental trials, with familiarisation using identical procedures to experimental trials. Familiarisation was separated from the experimental trials by 48 h, with 24 h of inactivity also separating each experimental trial. All trials commenced with 5 min of jogging at a pace standardised by a metronome to 132 beat/min, prior to four attempts at 12 different jump tests. From these attempts, 12 metrics of jump performance were calculated for each jump test. These metrics were calculated using the maximum, mean and median height/distance from different attempt combinations, with the first attempt being either recorded or a practice. The test-retest reliability of each jump performance metric derived from the jump tests was calculated between experimental trials one and two. Approximately 10 min after completing the jump tests in experimental trial two, boxers performed 3 x 2 min rounds of full contact sparring to induce fatigue. Construct validity was subsequently determined by comparing the decline in jump performance metrics between novice and experienced boxers over experimental trials two and three.

2.2. Participants

The study received institutional ethical approval from the Northumbria University Health and Life Sciences Research Ethics Committee and was conducted according to the Declaration of Helsinki. Fourteen male amateur boxers from Northumbria University Boxing Club provided their written informed consent to take part, after receiving a full verbal and written study explanation. Each boxer was unpractised at jump testing, free of lower extremity injury and had successfully passed an England Boxing medical for sparring. Seven boxers qualified as novice (stature 1.81 ± 0.08 m, body mass 82.7 ± 12.4 kg, age 20.9 ± 0.8 years), possessing under 6 months of training history and no inter-club sparring or competitive amateur boxing experience. Likewise, seven boxers qualified as experienced (stature 1.74 ± 0.12 m, body mass 71.3 ± 13.5 kg, age 22.0 ± 3.4 years), possessing over 18 months of training history and competitive experience including at least three inter-club sparring or competitive boxing bouts. Independent sample t-tests confirmed no difference between the groups in stature ($p = 0.22$), body mass ($p = 0.13$) or age ($p = 0.39$).

2.3. Procedure

Boxers commenced all trials by jogging for 5 min around a 10 m^2 square that was marked out by cones. The speed of jogging was standardised by a metronome to 132 beat/min, by instructing boxers to coincide their steps with the beat. The 12 jump tests were completed in the fixed order of bilateral vertical CMJ (BV-CMJ), left/right leg vertical CMJ, bilateral vertical SJ (BV-SJ), left/right leg vertical SJ, bilateral horizontal CMJ (BH-CMJ), left/right leg horizontal CMJ, bilateral horizontal SJ (BH-SJ), left/right leg horizontal SJ. Four attempts were completed for each jump test, with 15 s recovery between attempts and an additional 3 min of recovery between the vertical and horizontal jumps. For each unilateral jump, either the left or right leg was performed first according to random number generation.

All vertical jumps were recorded to 0.1 cm using an Opto Jump (Microgate, Bolzano, Italy), connected to a laptop computer

(Idea Pad 510, Lenovo, North Carolina, USA) running Opto Jump Next (Microgate, Bolzano, Italy). Boxers started with their feet approximately shoulder width apart and hands placed on hips. During the BV-CMJ, boxers squatted to a self-selected depth (established during familiarisation) before immediately jumping vertically for maximum height. For the BV-SJ, boxers squatted to a 90° knee angle that was measured by a goniometer (Cranlea, Birmingham, UK), before jumping vertically for maximum height following a 3 s pause with no countermovement. During both CMJ and SJ jumps, boxers were instructed to maintain knee and hip extension during flight, with slight knee and hip flexion permitted upon landing. Jumps were excluded if the boxers' hands did not remain on hips, or flexion of the hips or knees occurred during the flight phase. The left/right leg vertical CMJ and SJ were also performed identically to their bilateral counterparts, with the sole exception of requiring boxers to balance on their respective leg for 3 s prior to, and immediately after, jumping.

Horizontal jumps were recorded as the distance between a start line marked on the floor and the boxer's heel upon landing, measured to 1 cm using a tape measure (PowerWinder, Stanley, Slough, UK). Boxers started behind the start line with their feet approximately shoulder width apart and hands placed on hips. During the BH-CMJ, boxers squatted to a self-selected depth (established during familiarisation) before immediately jumping horizontally for maximum distance. For the BH-SJ, boxers squatted to a 90° knee angle that was measured by a goniometer (Cranlea, Birmingham, UK), before jumping horizontally for maximum distance following a 3 s pause with no countermovement. Jumps were excluded if the boxer's hands did not remain on hips or the feet did not land in a parallel stance. The left/right leg horizontal CMJ and SJ were also performed identically to their bilateral counterparts, with the sole exception of requiring boxers to balance on their respective leg for 3 s prior to, and immediately after, jumping.

The full contact sparring within experimental trial two was supervised by an England Boxing level two coach who provided maximal encouragement. Sparring occurred between two boxers in the same England Boxing recognised weight class, that also qualified for the same study group (i.e., novice v novice or experienced v experienced). A 7.32 m^2 ring (Competition Boxing Ring, Geezers, Norfolk, UK) and 453.6 g gloves (Sparring Gloves, ProBox, Gillingham, UK) were used, with boxers performing three rounds of 2 min exercise and 1 min rest. Immediately prior to sparring, boxers were permitted 10 min to undertake their own traditional pre-sparring warmup.

2.4. Statistical Analysis

Statistical analysis was performed using SPSS v26 with significance set at $p < 0.05$. After verification of underpinning assumptions, paired sample t-tests revealed no significant differences between the left and right leg for the vertical CMJ (p = 0.34), vertical SJ (p = 0.99), horizontal CMJ (p = 0.72) or horizontal SJ (p = 0.86). Therefore, only the left leg data were used and are hereby referred to as unilateral (i.e., UV-CMJ, UV-SJ, UH-CMJ and UH-SJ). From the four attempts completed per jump test, 12 metrics of jump performance were calculated using the maximum, mean and median height or distance achieved from different combinations of attempts, with the first attempt either being recorded or a practice (see Table 1). The test-retest reliability of each jump performance metric, from all the jump tests, was calculated using typical error (the standard deviation of the individual difference scores between trials ÷ square root of two) (Hopkins, 2000). Construct validity was determined using a 2 x 2 between and within group analysis of variance (ANOVA) between the novice and experienced boxers over trials two and three. For jump performance metrics where a significant group by time interaction effect was detected, Bonferroni adjusted confidence intervals were calculated on the difference between novice and experienced boxers' scores in trials two and three.

Table 1: Metrics of vertical jump height and horizontal jump distance that were calculated from four attempts at each jump test.

Metric	Attempt				Calculation
	1	2	3	4	
MAX 1	✓				Maximum height/distance from one recorded attempt.
MAX P+1	P	✓			Maximum height/distance from one recorded attempt after one unrecorded practice.
MAX 2	✓	✓			Maximum height/distance from two recorded attempts.
MAX P+2	P	✓	✓		Maximum height/distance from two recorded attempts after one unrecorded practice.
MAX 3	✓	✓	✓		Maximum height/distance from three recorded attempts.
MAX P+3	P	✓	✓	✓	Maximum height/distance from three recorded attempts after one unrecorded practice.
MEA 2	✓	✓			Mean height/distance from two recorded attempts.
MEA P+2	P	✓	✓		Mean height/distance from three recorded attempts after one unrecorded practice.
MEA 3	✓	✓	✓		Mean height/distance from three recorded attempts.
MEA P+3	P	✓	✓	✓	Mean height/distance from three recorded attempts after one unrecorded practice.
MED 3	✓	✓	✓		Median height/distance from three recorded attempts.
MED P+3	P	✓	✓	✓	Median height/distance from three recorded attempts after one unrecorded practice.

Note. ✓ = recorded attempt used in metric calculation, P = unrecorded practice attempt not used in metric calculation.

Table 2: Test-retest typical error of 12 metrics of jump height/distance calculated from eight jump tests, which were performed over two trials separated by 24 h of inactivity.

Metric	BV-CMJ (cm)	BV-SJ (cm)	UV-CMJ (cm)	UV-SJ (cm)	BH-CMJ (cm)	BH-SJ (cm)	UH-CMJ (cm)	UH-SJ (cm)
MAX 1	3.5	2.9	**1.7**	2.0	13	14	19	18
MAX P+1	3.0	3.1	2.3	1.4	13	11	19	17
MAX 2	3.2	2.5	1.9	1.6	12	11	15	17
MAX P+2	**1.5**	2.3	2.6	**1.3**	16	**10**	15	15
MAX 3	1.7	**2.2**	2.2	1.6	14	**10**	**13**	15
MAX P+3	2.0	2.8	2.2	1.5	**11**	**10**	**13**	16
MEA 2	2.9	2.5	1.8	1.6	**11**	12	17	16
MEA P+2	1.8	2.4	2.4	1.7	14	12	17	**13**
MEA 3	2.2	2.5	2.0	1.7	12	12	16	14
MEA P+3	2.0	2.5	1.9	1.6	13	11	14	15
MED 3	2.7	2.5	2.0	1.7	13	11	17	14
MED P+3	2.0	2.7	2.1	1.6	16	**10**	**13**	15

Note. **Bold** = lowest typical error per jump test, B = bilateral, U = unilateral, V = vertical, H = horizontal, CMJ = countermovement jump, SJ = squat jump. Refer to table 1 for metric calculations.

3. Results

The test-retest typical error of all metrics of jump performance, calculated from each jump test, are presented in Table 2. The lowest typical error recorded for each jump test was 1.5 cm (BV-CMJ), 2.2 cm (BV-SJ), 1.7 cm (UV-CMJ), 1.3 cm (UV-SJ), 11 cm (BH-CMJ), 10 cm (BH-SJ), 13 cm (UH-CMJ) and 13 cm (UH-SJ). The metrics of jump performance that most frequently produced the lowest typical error were the MAX P+2, MAX 3 and MAX P+3, with each metric producing the lowest recorded typical error for three jump tests. The MED P+3 produced the lowest typical error for two jump tests, with MAX 1, MEA 2 and MEA P+2 each producing the lowest typical error for one jump test.

Only three jump tests demonstrated construct validity by detecting a significant decrease in jump performance after sparring between trials two and three, as well as an interaction effect from boxers being categorised as novice or experienced (see Figure 1). For the BV-SJ, experienced boxers jump height was lower than novice boxers after sparring by 3.1 ± 1.0 cm (p = 0.03, 95% CI [0.5, 5.7] cm) for the MEA 2 and 3.0 ± 0.9 cm (p = 0.03, 95% CI [0.3, 5.4] cm) for the MED 3. Additionally, experienced boxers jump distance was lower than novice boxers after sparring on the UH-CMJ by 13 ± 3 cm (p = 0.04, 95% CI [1, 25] cm) for the MAX 3. Finally, experienced boxers jump height was also lower than novice boxers after sparring on the UV-SJ by 1.3 ± 0.3 cm (p = 0.04, 95% CI [0.1, 2.6] cm) for the MAX P+3, 2.0 ± 0.2 cm (p = 0.01, 95% CI [1.1, 3.0] cm) for the MEA P+2, 1.8 ± 0.5 cm (p = 0.01, 95% CI [0.1, 2.9] cm) for the MEA P+3, and 0.1 ± 0.1 cm (p = 0.02, 95% CI [0.4, 3.1] cm) for the MED P+3.

4. Discussion

The aim of this study was to examine the test-retest reliability and construct validity of various jump-test performance metrics for fatigue monitoring in amateur boxing. The jump performance metrics that most frequently produced the lowest typical error were the MAX P+2, MAX 3 and MAX P+3. Construct validity for monitoring fatigue was demonstrated by the BV-SJ MEA 2 and MED 3, the UH-CMJ MAX 3, plus the UV-SJ MAX P+3, MEA P+2, MEA P+3 and MED P+3. However, for the construct validity of these jump performance metrics to be considered meaningful, the 95% CI should exclude the respective typical error (i.e., the signal should exceed the noise of the test). The jump performance metric closest to achieving this was the UV-SJ MEA P+2, with all but 0.2 cm of the 95% CI [1.1, 3.0] cm being above the 1.3 cm typical error.

Unilateral jumps (UJ) appear more reliable and valid for fatigue monitoring than bilateral jumps (BJ). This is supported by the UV-SJ demonstrating the greatest potential for detecting construct validity beyond the respective typical error. Although UJ have previously been used to monitor limb asymmetries in athletes (Lockie et al., 2014), this study was the first to investigate their effectiveness at fatigue monitoring. The bilateral deficit provides one mechanism for UJ to more effectively monitor neuromuscular fatigue than BJ. The bilateral deficit describes a phenomenon whereby the force output from one leg during BJ is lower than the force output from one leg during UJ (Bobbert et al., 2006). This was evident during electromyography studies reporting greater neural activation of the quadriceps and hamstrings in one leg during UJ compared to BJ (Pappas et al., 2007). UJ may therefore be able to better stimulate neural drive than BJ, theoretically making it more sensitive to fatigue.

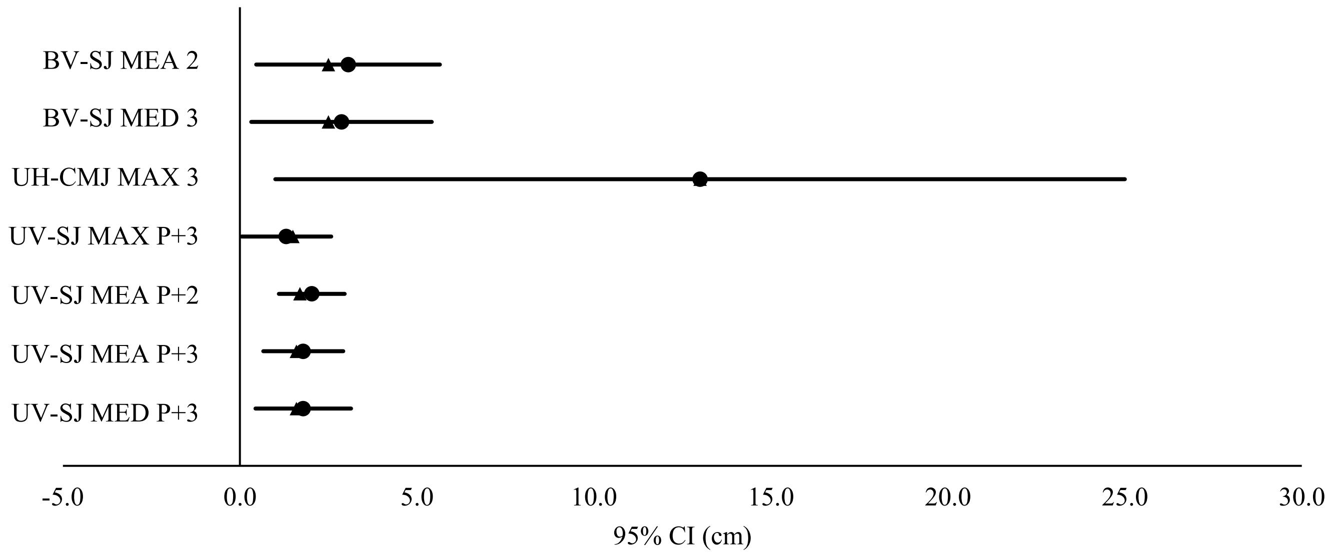

Figure 1: Forest plot of 95% confidence intervals (95% CI) showing the difference between novice and experienced boxers' jump height/distance from immediately prior to 24 h post sparring. All 95% CI indicate that experienced boxers' jump height/distance was lower than novices 24 h after sparring. *Note.* ● = mean difference, ▲ = test-retest typical error, B = bilateral, U = unilateral, V = vertical, H = horizontal, CMJ = countermovement jump and SJ = squat jump. Refer to Table 1 for metric calculations.

However, further research on the effectiveness of UJ for fatigue monitoring is needed before conclusive recommendations for use can be made.

Present findings also suggest that vertical jumps (VJ) are more reliable and valid for fatigue monitoring than horizontal jumps (HJ). This is because VJ consistently produced lower test-retest typical error than HJ. Furthermore, six of the seven jump performance metrics that demonstrated construct validity for fatigue monitoring were calculated from VJ tests. These findings concur with the wider literature reporting good validity of vertical CMJ and SJ for monitoring fatigue (Gathercole et al., 2015; Loturco et al., 2017; Oliver et al., 2015). However, the validity of HJ may have been expected because of greater biomechanical specificity to boxing movements (Delvecchio, 2011). One explanation for the poor validity and reliability of HJ, compared with VJ, may be the kinematic and kinetic differences that occur (Senshi et al., 2005). Kinematically, HJ produce higher anterior trunk lean, ankle dorsiflexion and knee extension than VJ (Senshi et al., 2005). This results in lower knee extension torque than is achieved during VJ (Senshi et al., 2005). Such biomechanical differences initiate different ground reaction forces (GRF), with VJ GRF directed almost entirely vertically, but HJ GRF directed horizontally and vertically (Seyfarth et al., 1999). Although the present study is limited by not measuring GRF, it can be speculated that VJ height may therefore be more valid for monitoring neuromuscular fatigue because all the neural drive is directed vertically and could therefore be better reflected in the resulting jump height. Whereas, during the HJ some of this neural drive may be lost as vertical GRF propulsion, which may not always therefore be reflected in jump distance. Further research is required to test this hypothesis though.

Present findings further indicate that the SJ appears more effective at fatigue monitoring than the CMJ. This was evident from six of the seven jumps that demonstrated construct validity for fatigue monitoring being SJ variations. This finding contradicts past evidence reporting that the CMJ and SJ were equally valid for monitoring fatigue (Loturco et al., 2017). This past research did however use force plates for determining jump height (Loturco et al., 2017), which are more accurate than the Opto Jump used in the present study (Glatthorn et al., 2011). Despite this, stretch shortening cycle (SSC) utilization and the length tension relationship (LTR) provide two explanations for SJ appearing superior to CMJ for fatigue monitoring. The SSC contributes additional force to increase jump height via factors such as tendon elasticity, in addition to neural drive (Nicol et al., 2006). Meanwhile, the LTR describes the variable force output that is produced at different muscle lengths, and by extension jump descent depth. The SJ eliminates the LTR by standardising descent depth to 90°, plus the SSC by pausing for 3 s. Consequently, it becomes less influenced by factors outside of neural drive and so may better reflect neuromuscular fatigue than CMJ height (Nicol et al., 2006).

Using three jump attempts appears best practice for fatigue monitoring. This is supported by the MAX P+2, MAX 3 and MAX P+3 metrics most frequently producing the lowest typical error, plus six of the seven jump performance metrics that demonstrated validity for fatigue monitoring also using three attempts. This finding supports multiple studies reporting that three jump attempts provided valid fatigue monitoring (Thorpe et al., 2015; Wiewelhove et al., 2017). Furthermore, the MEA P+2 demonstrated greatest potential for detecting changes greater than typical error, suggesting averages may be superior to maximum jump height. This is supported by the average of three attempts correlating significantly with footballers' training load, inferring validity for monitoring fatigue (Thorpe et al., 2015). Therefore, practitioners are encouraged to perform one practice UV-SJ, before using the average height from two recorded attempts to most effectively monitor fatigue in amateur boxing.

Opto Jump was used to measure jump height in this study because the system is highly portable and widely utilised in applied practice. While the Opto Jump demonstrates excellent test-retest reliability and validity in comparison to a gold standard force plate (Glatthorn et al., 2011), it should be noted that force plates remain the gold standard measure of jump performance because they enable an analysis of jump strategy via the force-time record that is not always reflected in the jump outcome of height/distance (Buckthorpe et al., 2012). Caution is therefore needed when comparing the findings of this applied study against results obtained in laboratory conditions using a gold standard force plate.

5. Conclusion

Based on the results of this study, practitioners seeking to monitor fatigue in amateur boxing should utilise a unilateral squat jump that is performed vertically. One unrecorded practice attempt should firstly be performed at this jump test, before taking the mean of two subsequent recorded attempts.

Conflict of Interest

The authors declare no conflict of interests.

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