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ORIGINAL ARTICLE

Development of a new fatigability jumping protocol: Effect of the test duration on reproducibility and performance

Développement d'un nouveau protocole d'induction de fatigue à base de sauts : effet de la durée sur la reproductibilité et la performance

J. Paulus[a,b,*], J.-L. Croisier[a,b], J.-F. Kaux[a], F. Tubez[a,b], D. Meyer[a], C. Schwartz[a,b]

[a] *Department of Physical Medicine and Rehabilitation, IOC Research Center for prevention and athlete health, FIFA Medical Center of Excellence, FIMS Collaborating Center of Sports Medicine, University and CHU of Liege, Quartier Blanc Gravier, Allée des Sports 2, 4000 Liège, Belgium*
[b] *Laboratory of Human Motion Analysis, University of Liege, Quartier Polytech, Allée de la Découverte 9, B52/3, 4000 Liège, Belgium*

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KEYWORDS
Countermovement jump;
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Reliability;
Fatigability protocol;
Anaerobic power.

Summary The Wingate Anaerobic Test (WAnT) and isokinetic fatigability protocols are mainly used to evaluate the anaerobic power of athletes for whom jumping is a predominant action in their sport. Nevertheless, the testing protocol must be as close as possible to the activity pattern of the sport to be valid. Therefore, for these athletes, the test should consist of repetitions of jumps that are task-specific. Our aim was to propose a new jumping protocol allowing for specific assessment of fatigue, to examine its absolute and relative reliability and to determine its ideal duration. Twenty male volleyball performed fifty countermovement jumps (CMJ) at a rate of 33 jumps per minute on two occasions, with seven days recovery between each session. Jump height was computed for each CMJ using a 3D optoelectronic system, which was subsequently added to determine cumulative performance after 10, 15, 20, 25, 30, 35, 40, 45 and 50 repetitions. Reliability of the average jump height was not affected by the lengthening of the protocol and was high for all considered durations (ICC > 0.94; SEM < 5%). A decrease in

* Corresponding author.
E-mail address: julien.paulus@uliege.be (J. Paulus).

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performance was directly and proportionally related to the duration of the fatigability protocol. Measuring average jump height during a protocol involving 25 CMJ at the rate of 33 jumps per minute appears to represent the best compromise between reliability, induced fatigue and physiological considerations. Moreover, until 25 repetitions, the partial sums by five repetitions can and should be used to further explore the subject's performance during the test.

MOTS CLÉS
Countermovement jump ;
Test-retest ;
Reproductibilité ;
Protocole de fatigabilité ;
Puissance anaérobie.

Résumé Le test anaérobie de Wingate (WAnT) et les protocoles isocinétiques de résistance à la fatigue sont majoritairement utilisés lorsqu'il s'agit d'évaluer la puissance anaérobie des athlètes pour lesquels le saut est une action prédominante dans leur pratique sportive. Néanmoins, le protocole de test se doit être le plus proche possible du schéma moteur du sportif pour être valable. Par conséquent, pour ces athlètes, le test devrait être constitué de sauts répétés, qui sont spécifiques à la tâche. Notre objectif était de proposer un nouveau protocole de sauts permettant d'évaluer spécifiquement la fatigue, d'examiner sa reproductibilité absolue et relative et d'en déterminer sa durée idéale. Vingt volleyeurs ont effectué cinquante contre-mouvement jump (CMJ) à une cadence de 33 sauts par minute à deux reprises, avec sept jours de récupération entre chaque séance. La hauteur des sauts a été calculée pour chaque CMJ à l'aide d'un système optoélectronique 3D, subséquemment intégrée pour déterminer les performances cumulées après 10, 15, 20, 25, 30, 35, 40, 45 et 50 répétitions. La reproductibilité de la hauteur moyenne de saut n'est pas affectée par l'allongement du protocole et est élevée pour toutes les durées considérées (ICC > 0,94 ; MEB < 5 %). La diminution de performance est directement proportionnelle à la durée du protocole de fatigabilité. La mesure de la hauteur moyenne de saut pendant un protocole impliquant 25 CMJ à la fréquence de 33 sauts par minute semble représenter le meilleur compromis entre fiabilité, fatigue induite et considérations physiologiques. De plus, jusqu'à 25 répétitions, les sommes partielles par cinq répétitions peuvent être utilisées pour explorer plus avant les performances du sujet pendant le test.

1. Introduction

Strength and conditioning trainers, coaches, clinicians and researchers have to frequently evaluate the anaerobic power of athletes either to monitor training status [1], produce more effective conditioning and training programs [2] or to validate the return to play process [3]. Several researchers have studied this anaerobic power by using the Wingate Anaerobic Test (WAnT) [4—7] or the isokinetic fatigability protocols [8], even with athletes who have to jump a large number of times in their sporting activity [9—12]. Indeed, jumping is an action conducted in many team sports, and for some of these it even represents the leading type of action [9—11]. However, Meckel, May-Rom [11] consider that the testing protocol must be as close as possible to the activity pattern of the sport to be valid. Therefore, to explore the anaerobic power of athletes for whom jumping is a predominant action and who perform several hundred jumps a week during practices and games [11,12], the test should consist of a repetition of jumps that are highly task-specific, and not in running or pedalling pattern.

To our knowledge, there are very few tests of this type, with the majority consisting of a continuous sequence of jumps [1,11,13—16]. In these conditions, the first jump of the sequence is a countermovement jump (CMJ), but the following jumps represent drop jumps (DJ) with variable starting heights since they depend on the previous jump. Since the drop height of the DJ influences the height reached during the jump [17], the fact that the CMJ (starting from the second jump) changes to DJs with various drop heights constitutes an evaluation bias. Only two studies explored a protocol of repeated maximal strict CMJs: McCaulley, Cormie [18] and Patterson, Raschner [19]. The first study compared the mechanical efficiency between different jumping conditions, including the CMJ, but did not explore the reproducibility of this protocol [18]. The characteristics of the test of the second study make it very specific to alpine skiing and therefore it does not specifically explore anaerobic power for jump-dominated sports. More specifically, it consists of sixty repeating CMJs occurring every two and a half seconds (for two and a half minutes in total) with an additional load equivalent to forty percent of the subject's bodyweight [19].

The aim of our study was to propose a test to specifically assess the fatigue of athletes for which jumping is a predominant action, and to determine its reproducibility, which is a key factor in a test validation process [20].

2. Methods

2.1. Experimental approach to the problem

A repeated-measures design was used to evaluate the test-retest reliability of jump height for a fatigability jumping protocol. After warm-up and familiarization, twenty male volleyball players performed fifty CMJs at a rate of 33 jumps per minute. The test-retest testing sessions were separated by seven days, and the protocols were identical between sessions.

2.2. Subjects

Twenty male volleyball players, with no history of lower limb or spine injury, practicing more than four hours of competitive volleyball (training included) per week for a minimum of two years were included in this study. The mean age, size and body weight ± SD were 23.6 ± 2.3 years, 187.7 ± 6.6 cm and 77.5 ± 8.5 kg, respectively. At the time of the study, all volunteers were declared fit for practice by the sport medical staff of their team. This study was conducted in conformity with ethical standards and approved by the Ethics Committee of the University and Faculty Hospital of Liège.

2.3. Procedures

Two identical repeated maximal CMJ sessions were performed by each subject at the same time of day, to avoid any impact of circadian rhythmicity, with seven days between each session. All sessions were executed under the direction and encouragement of the same researcher. To avoid possible effects of residual fatigue due to recent exercise, subjects were asked to refrain from physical activity for forty-eight hours prior to each evaluation session. In order to standardize the test conditions as much as possible, subjects were asked to follow a stable sleep schedule in the previous few days before the sessions, to not eat any heavy meals in the three hours preceding the test and to not drink coffee, tea or any other energy drink on the day of the test.

2.4. Instrumentation

The jump height of each repetition was measured using a 3D optoelectronic system (Charnwood Dynamics, Rothley, UK) composed of four CX1 sensor units and two active (infrared) markers. This 3D system has been shown to be an accurate evaluation tool [21]. The markers were placed on the right and left posterior superior iliac spine. Data were acquired at 200 Hz.

2.5. Exercise testing

The subjects performed a warm-up consisting of two sets of eight regular unloaded squats and eight sumo unloaded squats (with twenty seconds rest between each set), two minutes of single under jump rope, three sets of high stepping box on one foot (sixty at moderate intensity, sixty at high intensity and thirty at very high intensity with forty-five seconds of rest between each set) and five maximal CMJs with thirty seconds rest between each repetition. Afterwards, a familiarization protocol composed of one set of eight and one set of five submaximal CMJs, with thirty seconds of rest between each set, was performed by each subject under the conditions of the test.

The fatigability protocol consisted of the repetition of fifty CMJs at a rate of 33 jumps per minute. A metronome, with a visual and audio signal, guaranteed adherence to the requested rhythm. This jump frequency was chosen according to the duration of each CMJ's phase as reported by other studies:

500 ± 9.4 ms (range of 321 to 795 ms) from the preparatory phase to touchdown [22],

- 144 ± 34 ms for the impact absorption phase [23];
- 290 ± 40 ms for the push-off phase [24];
- 586 ms for the flight time [15].

A number of control tests (unpublished data) were done to ensure that this pace was achievable by all subjects.

To insure that all jumps were CMJs and not drop jumps or squat jumps, after the consecutive triple-flexion (ankle, knee and hip) of the landing phase the subject was asked to fully extend his lower limbs and wait for the signal to engage the next CMJ. The subjects held a wooden stick on their shoulders to neutralise any coordination effects between the lower and upper limbs [25]. No feedback regarding the height of jump was given to the subjects during the test.

Throughout the fatigability protocol, subjects were asked to jump as high as possible for the first CMJ and during each subsequent repetition. To motivate the subjects, the researcher verbally and intensely encouraged them throughout the test.

2.6. Data analysis and statistical analysis

The jump height was defined as the difference between the highest position of the barycentre of the right and left posterior superior iliac spine during jumping and the height of this barycentre during a static standing position. 3D marker positions were filtered through a zero-phase 4th order low-pass Butterworth filter at a cut-off frequency of 10 Hz [21].

For the five maximal CMJs before fatigability testing, only the best repetition was analysed. This is defined as the highest jump out of the five CMJs. For the fatigability protocol, the jumping height wuas computed for each CMJ and subsequently summed to compute cumulated performance after 10, 15, 20, 25, 30, 35, 40, 45 and 50 repetitions. Moreover, we calculated the partials sums by five (and ten where appropriate) repetitions as well as the fatigue induced by the protocol as a percentage (Equation 1). $\frac{Worst\ \ repetition-Best\ \ repetition}{Best\ \ repetition} * 100$(Equation 1)

The normality of distribution of the data was verified using the Shapiro-Wilk test. When this was violated, data were log-transformed (provided that the normality of the distribution of log-transformation was verified). Systematic bias, which refers to a general trend for measurements to be different in a particular direction when compared between repeated tests, was assessed with a general linear model for repeated measures ANOVA. The compound symmetry was checked by the Mauchley test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse—Geisser or Huynh-Feldt procedure (when the epsilon correction factor was respectively lower or higher than 0.75). Statistical significance was set at a P-value < 0.05 level for all analysis and confidence intervals were fixed to 95%. All calculations were made with Statistica 10 (Statsofts, Tulsa, OK), MedCalc

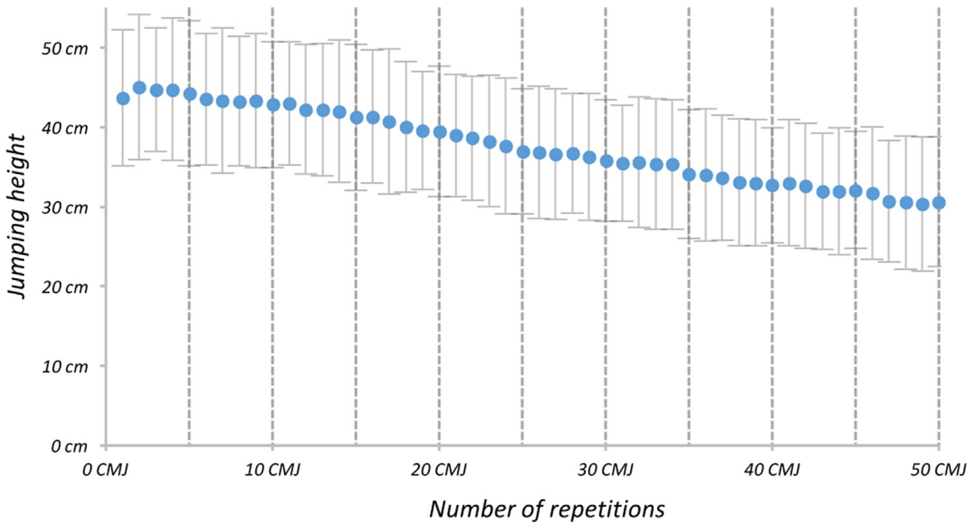

Figure 1 Relationship between the jumping height and the number of repetitions during the first trial. Data are reported as mean ± standard deviation.

Table 1 Coefficient of determination of the linear model for the decrease in performance for the first trial.

Number of CMJs	Mean ± SD of R^2	Number of CMJs	Mean ± SD of R^2
10 CMJ	0.73 ± 0.17	35 CMJ	0.86 ± 0.12
15 CMJ	0.67 ± 0.23	40 CMJ	0.89 ± 0.10
20 CMJ	0.69 ± 0.24	45 CMJ	0.91 ± 0.09
25 CMJ	0.77 ± 0.19	50 CMJ	0.93 ± 0.08
30 CMJ	0.83 ± 0.14		

13.3.3 (MedCalc Software, Ostend, Belgium) and Excel 2013 (Microsoft, Redmond, WA).

Relative reliability was determined using the ICC (2,1) (single measures) (Intraclass correlation), which assesses rating reliability which represents the proportion of variance in a set of scores that is attributable to the true score variance. An ICC higher than 0.90 is considered to be excellent, between 0.70 and 0.89 to be high and between 0.50 and 0.69 to be moderate [26]. Saenz, Avellanet [27] have suggested that an ICC value higher than 0.80 is highly reliable and acceptable for clinical work. ICC is presented as a value along with its 95% CI.

The absolute reliability, related to the variation of the value of a parameter, was assessed by Standard Error of Measurements (SEM). Equation 2 was taken as the criterion for acceptable precision [28].$SEM \leq \frac{SD}{2}$ (Equation 2)

3. Results

The Fig. 1 illustrates the decrease in CMJ height across the fifty repetitions during the first trial.

The decrease in the performance (Equation 1), presented in Table 2, is proportionally related to the number of repetitions (or the duration) of the fatigability protocol. The coefficient of determination (R^2), or goodness-of-fit of the linear model, is presented in Table 1 for the first trial while the percentage decrease in performance is provided in Table 2.

The relative reproducibility was very high for all the durations, with the ICC ranging from 0.943 [0.860/0.978] (50 CMJ) to 0.969 [0.921/0.988] (15 CMJ) (see Table 2). Likewise, the relative reproducibility of all partials sums by five or ten repetitions was very high, with the ICC ranging between 0.893 [0.745/0.958] and 0.967 [0.916/0.987] (see Table 3).

Similar to the relative reproducibility, the absolute reproducibility was very high for all considered durations, with the SEM ranging between 3.44% and 4.88% (see Table 2*)* and in accordance with the criterion for acceptable precision for all durations (see Equation 2). The SEM ranged between 3.25% and 6.85% for the partial sum by five and ten repetitions (see Table 3). Except for the last three partial sum by ten repetitions (21 to 30 CMJ, 31 to 40 CMJ and 41 to 50 CMJ), the criterion for acceptable precision (see Equation 2) was met.

The best jump height of the fatigability protocol (46.8 ± 9.0 cm and 46.9 ± 8.2 cm for the test and retest, respectively) represents 96.5 ± 4.5% and 96.1 ± 3.% of the five best maximal CMJs made before fatigability testing for the test and retest, respectively.

4. Discussion

Many sports require the evaluation of fatigue resistance capacities, termed the anaerobic lactic energy system. Ideally, the testing protocol should be as close as possible

Table 2 Test's duration, decrease's percentage of performance (Error! Reference source not found.), mean ± SD of CMJ height (test and retest respectively on the first and second line), SEM and ICC [CI 95%] between the test and retest of fatigability jumping protocol for 10 to 50 CMJ by shift of five repetitions.

Number of CMJ	Test's duration	Decrease's percentage	Mean ± SD of CMJ height	SEM absolute (relative)	ICC [CI 95%]
10 CMJ	18.2 s	−13.5 ± 5.7%	44.0 ± 8.4 cm 43.8 ± 7.7 cm	1.56 cm (3.56%)	0.967 [0.916/0.987]
15 CMJ	27.3 s	−15.9 ± 6.1%	43.4 ± 8.3 cm 43.1 ± 7.5 cm	1.49 cm (3.44%)	0.969 [0.921/0.988]
20 CMJ	36.4 s	−19.8 ± 6.1%	42.6 ± 8.2 cm 42.3 ± 7.4 cm	1.57 cm (3.70%)	0.964 [0.910/0.986]
25 CMJ	45.5 s	−23.5 ± 5.5%	41.7 ± 8.2 cm 41.4 ± 7.2 cm	1.61 cm (3.87%)	0.961 [0.902/0.985]
30 CMJ	54.5 s	−26.3 ± 6.3%	40.8 ± 8.1 cm 40.5 ± 7.0 cm	1.70 cm (4.18%)	0.955 [0.888/0.983]
35 CMJ	63.6 s	−29.5 ± 6.3%	40.0 ± 8.0 cm 39.7 ± 6.9 cm	1.74 cm (4.38%)	0.952 [0.880/0.981]
40 CMJ	72.7 s	−32.3 ± 6.7%	39.2 ± 8.0 cm 38.9 ± 6.8 cm	1.76 cm (4.52%)	0.950 [0.875/0.980]
45 CMJ	81.8 s	−35.3 ± 7.3%	38.4 ± 7.9 cm 38.2 ± 6.7 cm	1.80 cm (4.71%)	0.946 [0.866/0.979]
50 CMJ	90.9 s	−37.9 ± 8.2%	37.6 ± 7.9 cm 37,5 ± 6.6 cm	1.83 cm (4.88%)	0.943 [0.860/0.978]

to the activity pattern of the considered sport [11,29]. Nonetheless, the tests classically used to explore anaerobic power in sports where the leading type of action is jumping are the isokinetic fatigability protocol [8], WAnT [4—7] or the continuous jumping fatigability protocol [1,11,13—16]. The isokinetic movement during fatigability protocol and the pedalling pattern are exclusively concentric while the jumping pattern in sports activities is composed of an alternating cycle of eccentric-concentric contractions, called the stretch-shortening cycle [16]. The jumping fatigability protocols previously developed [1,11,13,16] consisted of a continuous sequence of jumps. In these conditions, the first jump of the sequence is a CMJ, but the following jumps are DJs with variable starting heights, since they depend on the performance of the previous jump. It should be noted that DJs are less frequent than CMJs, and that jump improvements due to training are task specific [30]. Thus, a more specific test is required. A jumping fatigability protocol with strict CMJs is in accordance with the activity pattern of the considered sport and therefore is more task specific.

The requested rhythm of our protocol (33 jumps per minute, with each jump engaged approximately every 1.82 seconds) ensures that each jump is a strict CMJ via the return to a standing position between the landing phase of a CMJ and the lower limb's triple flexion during the preparation phase of the next jump. Our testing design, by improving the task-specific characteristics, represents a new step compared to the previously developed protocols. The aim of this study was to examine absolute and relative reliability of a novel fatigability jumping protocol for 10 to 50 CMJs with shifts of five repetitions, to determine the optimal compromise between reproducibility, physiological considerations and fatigue induction.

It would make sense that lengthening the jumping protocol results in greater interference in the motivational aspect of the performance, thus potentially negatively affecting the reliability of the jumping height. Nevertheless, our data based on a specialized population of volleyball players, in accordance with previous studies [31], indicates that this is not the case. Indeed, an original finding of our study is that the lengthening of the fatigability protocol does not affect the relative and absolute reproducibility of cumulative jumping height, which were excellent. If we consider only this observation, the number of repetitions as such does not seem to be a crucial factor in the fatigability jumping protocol. The test-retest reproducibility of our fatigability jumping protocol is within the same range as the 30-s continuous jump test of Dal Pupo, Gheller [1] (SEM = 2.49% and ICC = 0.98 [95% CI: 0.95/0.99] for the mean height, considering all jumps) and the 60-s continuous jump test of Bosco, Luhtanen [32] (Pearson correlation coefficient = 0.95 with a *P*-value lower than 0.001 for all parameters), even if the

Table 3 Mean ± SD of CMJ height (test and retest respectively on the first and second line), SEM and ICC [CI 95%] between the test and retest of fatigability jumping protocol for partials sum by five and ten repetitions.

Partials sum	Mean ± SD of CMJ height	SEM absolute (relative)	ICC [CI 95%]
1 to 5 CMJ	44.5 ± 8.6 cm 44.6 ± 8.0 cm	1.60 cm (3.60%)	0.960 [0.900/0.985]
6 to 10 CMJ	43.4 ± 8.2 cm 43.1 ± 7.4 cm	1.45 cm (3.36%)	0.964 [0.909/0.986]
11 to 15 CMJ	42.2 ± 8.4 cm 41.7 ± 7.2 cm	1.61 cm (3.84%)	0.955 [0.888/0.983]
16 to 20 CMJ	40.2 ± 8.2 cm 39.6 ± 7.1 cm	2.06 cm (5.17%)	0.923 [0.812/0.970]
21 to 25 CMJ	38.1 ± 8.0 cm 37.9 ± 6.6 cm	1.81 cm (4.77%)	0.935 [0.840/0.975]
26 to 30 CMJ	36.5 ± 7.9 cm 36.1 ± 6.3 cm	2.27 cm (6.26%)	0.893 [0.745/0.958]
31 to 35 CMJ	35.2 ± 7.9 cm 34.8 ± 6.5 cm	1.97 cm (5.63%)	0.922 [0.809/0.969]
36 to 40 CMJ	33.3 ± 7.8 cm 33.6 ± 6.2 cm	1.90 cm (5.68%)	0.924 [0.813/0.970]
41 to 45 CMJ	32.3 ± 7.6 cm 31.9 ± 6.0 cm	2.14 cm (6.65%)	0.897 [0.753/0.959]
46 to 50 CMJ	30.8 ± 8.1 cm 31.2 ± 6.3 cm	2.12 cm (6.85%)	0.909 [0.780/0.964]
1 to 10 CMJ	44.0 ± 8.4 cm 43.8 ± 7.7 cm	2.85 cm (3.25%)	0.967 [0.916/0.987]
11 to 20 CMJ	41.2 ± 8.2 cm 40.7 ± 7.1 cm	3.61 cm (4.41%)	0.942 [0.856/0.977]
21 to 30 CMJ	37.3 ± 7.9 cm 37.0 ± 6.5 cm	3.96 cm (5.34%)	0.920 [0.806/0.969]
31 to 40 CMJ	34.2 ± 7.8 cm 34.2 ± 6.3 cm	3.76 cm (5.49%)	0.926 [0.820/0.971]
41 to 50 CMJ	31.6 ± 7.8 cm 31.6 ± 6.1 cm	4.19 cm (6.63%)	0.906 [0.773/0.963]

statistical analysis of Bosco, Luhtanen [32] can be described as weak [1]. Regarding our protocol, the relative and absolute reproducibility of the partials sums by five repetitions is excellent regardless of the interval considered, up until twenty-five repetitions. If we rely on the reproducibility analysis, the partials sums by ten repetitions could also be used, however its relevance and analytic precision is lower than the partial sums by five repetitions (up until twenty-five repetitions). We used jumping height and not mechanical power [16,32] to analyse the reproducibility of the fatigability jumping protocol due to fact that the height of a vertical jump is the most direct and thus finest measure for assessing performance and controlling training effects. Moreover, the jumping height has a more practical utilization and relevance for coaches and athletes than mechanical power [1].

A key point in the process of determining the optimal number of jumps is the aerobic contribution to energy metabolism: up until forty-five seconds, the aerobic contribution is about 37% (± 4%), while if the test lasts sixty seconds, this contribution increases to 45% (± ≈ 5%) [33]. Therefore, considering that the test reproducibility is influenced very little by the duration of the test, twenty-five jumps should represent the maximum number of jumps achievable. Indeed, this protocol duration (45.5 seconds) corresponds to the recommendations of Dal Pupo, Gheller [1] who explained that an anaerobic test longer than forty five seconds induces serious discomfort and can overestimate the power output due to the failure of many subjects to comply with the ''all-out'' characteristic of the test. In addition, this duration is in accordance with the study by Green [34] who explains that in an all-out test, the work performed from the forty-fifth second onward is fuelled predominately by oxidative metabolism and ''therefore diminishes the accuracy with which total work output measures anaerobic work capacity''. Moreover, Bosquet, Maquet [31] point to the fact that performance enhancement in a test that lasts more than forty-five or fifty seconds is laborious to interpret as it can be due to an improvement in anaerobic metabolism, aerobic metabolism or a mix of both.

The fatigue inducted by the jumping protocol is directly and linearly proportional to the number of CMJs. Indeed, the coefficient of determination (R^2) for the linear model between the decrease in performance and the number of repetitions (or the duration) for the fatigability protocol is good to very good since, for twenty-five repetitions, 77% of the induced fatigue can be explained by the number of jumps. After twenty-five jumps, the performance decreased on average by 23.5 ± 5.5%, which is lower than the fatigue induced by an all-out knee isokinetic test (33.35 ± 7.85%

and 47.25 ± 7.67% for 20 and 30 repetitions, respectively [31]) or a WAnT (49.1% and 47.0 ± 7.6% for Coppin, Heath [35] and Zupan, Arata [36], respectively). This decreased fatigue induced by our protocol may be explained by (1) the task dependency which can strongly modulate the observed fatigue [37], (2) the higher efficiency of the stretch-shortening cycle (SSC) than that observed when shortening is not preceded by lengthening contraction (eccentric) such as during WAnT or isokinetic knee contraction [13] and (3) fewer allowed anatomical compensations by the isokinetic knee flexion-extension (due to straps at the thigh, pelvis and shoulders) and by the pedalling pattern (due to seated position [38]) as compared to the jumping pattern. Indeed, these factors do not allow the same biomechanical compensation as during the (polyarticular) jump movement, which could limit the impact of fatigue by means of compensation strategies. In any case, the fatigue induction observed in our study is similar to the data reported previously by Rodacki, Fowler [39] (a 29.1 ± 4.0% decrease in jump height after 30.6 ± 6.9 continuous jumps) and Dal Pupo, Gheller [1] (a 23.5 ± 6.9% and 25.5 ± 5.0% decrease in jump height after 26.6 ± 1.9 and 26.6 ± 1.8 continuous jumps for test and retest, respectively). The induced fatigue of our protocol, for twenty-five jumps, ranged between a minimum of 13.4% and a maximum of 42.5%. This range of values allows for the distinguishing of subjects with good fatigue resistance capacities from those with lower capacities, therefore making our protocol sufficiently discriminating to individualize training sessions depending on the profile of the athlete, or to control the effect of a training period or performance-enhancing supplementation. Consequently, a duration of twenty-five jumps seems to be the best compromise between reliability and physiological considerations while inducing enough fatigue to be discriminant. However, if necessary, the number of jumps of the protocol can potentially be increased (up to 50) according to the needs of strength and conditioning trainers, clinicians and researchers who wish to analyse various markers after induction of different levels of fatigue (see Table 2 for the decrease in percent performance according to number of jumps performed).

The maximal CMJ height of our subjects is similar to that of subjects of Dal Pupo, Gheller [1] (50.5 ± 5.3 and 51.1 ± 6.5 for test and retest, respectively) but higher to that of subjects of Rodacki, Fowler [39] (33.4 ± 4.4 cm) due to differences between the populations (male subjects actively engaged in various sports vs. competitive volleyball players). During the fatigability jumping protocol, the best repetition was always among the first five jumps (mean ± SD: 3.1 ± 1.4 repetitions) and, if we consider a fatigability protocol duration of twenty-five jumps, the worst repetition was among the last three for sixteen of twenty subjects (mean ± SD: 23.1 ± 2.8 repetitions). Each of the twenty subjects, during the test or the retest, managed to keep up with the requested jumping rhythm whether be it at the beginning of the test when the jump height, and so the flying time, was important or at the end of the test when the fatigue was felt. Indeed, the duration of the preparation phase, the flying time and the landing phase takes 1.32 ± 0.08 seconds while each jump was engaged every approximately 1.82 seconds. Therefore, the waiting phase in the standing position between the landing of a jump and the triple-flexion of the preparation phase of the subsequent jump lasts 0.50 ± 0.08 seconds. This duration cannot be considered, strictly speaking, as rest due to its shortness and the cognitive attention required to respect the rhythm. The rhythm of 33 jumps per minute seems suitable since it ensures that each jump is a strict CMJ without introducing any real rest between jumps.

In this validation study, we used a 3D optoelectronic system for the measurement of jumping height. However, despite slight measurement errors (underestimation of about 1 cm for Optojump compared to force plate [40]), other devices based on flying time can be eventually used in place of 3D system [40]. Another limitation was that the pattern of jump used in this protocol was not totally task-specific to a specific sport due to the fact that it must allow inter-sport comparisons. Indeed, the jump patterns in volleyball, basketball, handball, soccer and so on are not completely identical. To be able to use only one jumping protocol to compare fatigability resistance between sports, we had to strike a satisfying compromise between specificity and cross-sectional use. However, it still remains more specific than the pattern of jumps used in previously developed protocols. Finally, this study was conducted with a specialized population of volleyball players, who are trained to perform the vertical jump. Our results should also be confirmed in a non-specialized population.

5. Practical applications

- The duration of the fatigability protocol does not affect the relative and absolute reproducibility of cumulative jumping height;
- twenty-five jumps represents the best compromise between induced fatigue, reliability and physiological considerations;
- the partials sums by five repetitions can and should be used to further explore the subject's performance during the test;
- the induction of fatigue is directly proportional to the number of CMJs and thus also to the length of the protocol;
- to our knowledge, no previous fatigability jumping protocol observes the task specific conditions needed to explore the anaerobic power of athletes for which jumping is a predominant action;
- the testing protocol must be as close as possible to the activity pattern of the considered sport. Our protocol ensures that each jump is a strict CMJ and therefore meets the task specific condition.

Disclosure of interest

The authors declare that they have no competing interest.

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