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Review

The countermovement jump to monitor neuromuscular status: A meta-analysis

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ABSTRACT

Objectives: The primary objective of this meta-analysis was to compare countermovement jump (CMJ) performance in studies that reported the highest value as opposed to average value for the purposes of monitoring neuromuscular status (i.e., fatigue and supercompensation). The secondary aim was to determine the sensitivity of the dependent variables.
Design: Systematic review with meta-analysis.
Methods: The meta-analysis was conducted on the highest or average of a number of CMJ variables. Multiple literature searches were undertaken in Pubmed, Scopus, and Web of Science to identify articles utilizing CMJ to monitor training status. Effect sizes (ES) with 95% confidence interval (95% CI) were calculated using the mean and standard deviation of the pre- and post-testing data. The coefficient of variation (CV) with 95% CI was also calculated to assess the level of instability of each variable. Heterogeneity was assessed using a random-effects model.
Results: 151 articles were included providing a total of 531 ESs for the meta-analyses; 85.4% of articles used highest CMJ height, 13.2% used average and 1.3% used both when reporting changes in CMJ performance. Based on the meta-analysis, average CMJ height was more sensitive than highest CMJ height in detecting CMJ fatigue and supercompensation. Furthermore, other CMJ variables such as peak power, mean power, peak velocity, peak force, mean impulse, and power were sensitive in tracking the supercompensation effects of training.
Conclusions: The average CMJ height was more sensitive than highest CMJ height in monitoring neuromuscular status; however, further investigation is needed to determine the sensitivity of other CMJ performance variables.

1. Introduction

The countermovement jump (CMJ) has been one of the most used tests for monitoring neuromuscular status in individual,[1–6] and team sports,[6–11] as well as the military.[12–16] A number of researchers have found CMJ performance to be an objective marker of fatigue and supercompensation[1,4,17,18]; however, others have reported mixed results utilizing CMJ measurements.[3,7,19,20] The disparity in findings could be attributed to a combination of general and specific factors. General factors may include: population type, intervention duration, and intensity of the activity performed. Specific CMJ performance factors include the reporting of a number of different kinematic and kinetic variables (e.g. jump height, peak power, relative peak power, relative power, mean power, peak velocity, peak force, mean force, rate of force development, eccentric time/concentric time, flight time/eccentric time, and flight time/contraction time using an unloaded and/or loaded CMJ).[6,8,9,21,22] In addition, it appears that, some variables are more sensitive than others for determining an athlete's neuromuscular status.[8,9]

The use of highest and average values to assess and monitor CMJ performance has been identified as another confounding factor.[23] Statistically, the researcher or practitioner has a much higher probability (∼10:1) of finding the true score when the average value is

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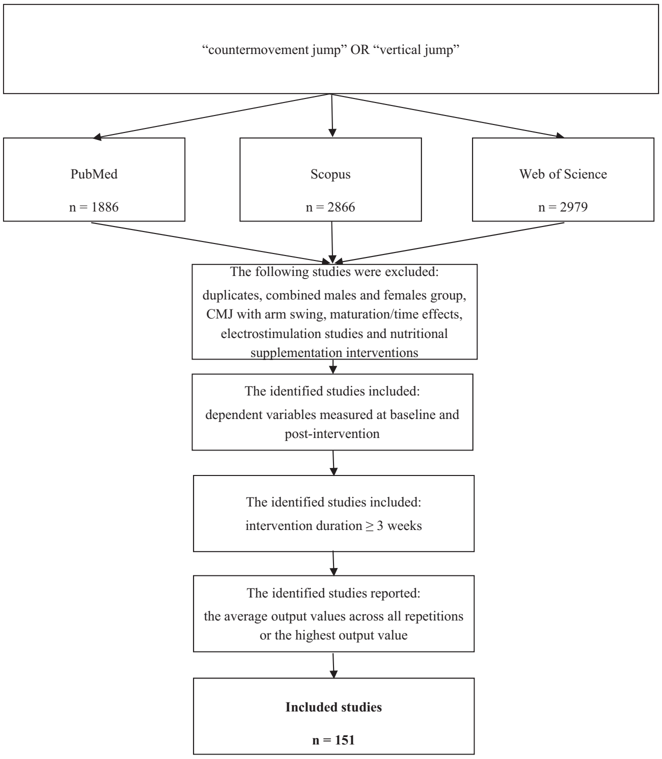

Fig. 1. Search strategy.

used over the highest value.[24,25] Finding the true score is essential when monitoring an individual's "real" performance change.[26–28] There is minimal research investigating the benefits and limitations of reporting highest vs. average values during CMJ assessment and monitoring[29] or with other performance tests,[30] and the limitation of these studies is the failure to quantify the magnitude of differences (e.g., the effect size synthesized by meta-analysis). Given the identified limitations, the primary aim of the meta-analysis was to compare the utility of the CMJ for monitoring neuromuscular status in studies that reported the highest value as opposed to average value. The secondary aim was to determine the sensitivity of the dependent variables to detect changes in CMJ performance and neuromuscular status.

2. Methods

Literature search: one author conducted the literature search, collated the abstracts and applied the initial inclusion criteria. All peer-reviewed journal articles that used the CMJ to monitor neuromuscular status (i.e. fatigue and/or supercompensation) following a chronic intervention (i.e., ≥3 weeks) were included in the initial analysis. The fatigue and supercompensation analyses were performed according to the initial purpose of each study. Fatigue was defined as the inability to maintain performance at the required level,[9,11] due to the effects of the chronic intervention. The supercompensation effect was defined as an overshoot in performance of baseline measures following adequate recovery after a training stimulus.[31] The following keywords were used during the electronic search: "countermovement jump" or "vertical jump". The following electronic databases were searched on 18th of February 2015: PubMed; Scopus; and Web of Science (Fig. 1). The search was not limited to specific years. The search strategy included studies investigating all training modalities and all kinematic and kinetic variables used to assess CMJ performance.

Inclusion criteria: during the second phase of study selection, the inclusion criteria were as follows: (i) studies must be written in English; (ii) studies tested CMJ at baseline and post-intervention and the results presented as mean and standard deviations; (iii) the highest and/or average (of all available repetitions[32]) kinematic (e.g., jump height, velocity, and time dependent variables) and/or kinetic (e.g., force, power, and rate of force development) variables were reported in the methods and results sections; (iv) the duration of the intervention was greater than or equal to three weeks; and, (v) participants were healthy male and/or female and split into distinct groups.[5,33] Articles that involved CMJ performance with arm swing,[34,35] had a maturational or time effect,[36,37] administered electrostimulation,[38,39] and/or provided nutritional supplementation[12,40] were excluded. If pertinent data were absent, the authors were contacted and the necessary information was requested via e-mail. If the original data were not provided by the authors, the mean and standard deviations were extracted from graphical representation using the tool *ycasd*[41] or estimated from the median, range, and sample size.[42] During the third phase of study selection, two authors reviewed and identified the titles and abstracts based on the above inclusion criteria. In the final phase, a fourth author was asked to review the selected articles for inclusion in the meta-analysis.

Study quality: the Consolidated Standards of Reporting Trials (CONSORT) statement was used for checking the quality of reporting[43] by one author. The 25 items identified in the CONSORT criteria could achieve a maximal score of 37. The items are distributed in sections and topics such as: "Title and abstract"; "Introduction" (Background and objectives); "Methods" (Trial design, Participants, Interventions, Outcomes, Sample size, Blinding, Statistical methods); "Results" (Participant flow, Recruitment, Baseline data, Numbers analysed, Outcomes and estimation, Ancillary analyses, Harms); "Discussion" (Limitations, Generalisability, Interpretation); "Other information" (Registration, Protocol, Funding).

Statistical analysis: heterogeneity of the included studies was evaluated by examining forest plots, confidence intervals, and I^2. I^2 values of 25, 50, and 75 indicate low, moderate, and high heterogeneity, respectively.[44] Random effects were analysed using the DerSimonian and Laird approach.[45] The meta-analysis was conducted based on the number of CMJ performance variables that have been used to monitor fatigue and/or supercompensation, and when permitted, comparisons between the subgroups highest and average CMJ were performed. Statistical significance was set at a level of $P \leq 0.05$ and the magnitude of differences for each dependent variable and between the subgroups were calculated using ES with 95% CI.[45] The sensitivity of the CMJ for monitoring changes in neuromuscular status was quantified using ES (Large effect >0.80; moderate effect 0.20–0.80; small effect <0.20).[46] The CV (i.e., [standard deviation ÷ mean] × 100,[47] with 95% CI)[48] of each CMJ variable was calculated to interpret its respective level of instability.[49] A scale for the CV has been suggested with CV >30% = large and CV <10% = small.[50] Variables with a large CV are less likely (odds ratio) to detect statistically significant differences during repetitive measurements.[51] All data were analysed using CMA v3 (Biostat, New Jersey, USA) and Excel 2013 worksheet (Microsoft, Washington, USA).

3. Results

Overview of articles included: an initial search produced a possibility of 7731 articles (Fig. 1). After inclusion criteria were applied, 151 articles were included for the final analysis. One hundred and twenty nine articles used the highest output value (i.e., 85.4%),[17,52–60,61–179] twenty articles used the average output value

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(13.2%)[2,180–198] to measure, assess, and monitor CMJ performance and two articles reported both (1.3%).[29,199]

Publication bias: among the articles included, 52% of the overall interventions resulted in non-significant ($p > 0.05$) differences to the baseline assessments, when all the variables were included in the analysis (i.e., 278 intervention with non-significant differences ÷ 531 overall interventions = 52%). When the same analysis was performed, the non-significant results were found to differ markedly between the highest CMJ (272 ÷ 491 = 55%) and average CMJ (6 ÷ 40 = 15%).

Quality of articles: quality assessment of the 151 included articles ranged from 38% to 70% with a mean CONSORT rating of 51%.[43] Fifty nine percent of the included studies had ratings exceeding 50%. Ethical approval had been obtained in all studies.

Participant characteristics: the pooled sample size for this meta-analysis was 4834, 73% of participants were in an intervention group and the remaining 27% served as controls. The age ranged from 8 ± 1[198] to 82 ± 3 years[71] with a pooled sample mean of 23 ± 12 years. One article did not report the participants' age.[90] Male subjects (80%) were utilized more so than females (20%). Sixty percent of the subjects were athletes. The athletes were involved in 21 sports: soccer (49%), basketball (10%), track and field (8%), volleyball (5%), handball (5%), judo (3%), rugby union (3%), tennis (2%) water polo (2%), alpine skiing (1%), American football (1%), Australian rules football (1%), ballet (1%), baseball (1%), cross country skiing (1%), dance majors (1%), lacrosse (1%), softball (1%), taekwondo (1%), weightlifters (1%), and wrestling (1%). The non-athletic participants (40%) included; physically active individuals (37%), physical education/sports science students (32%), sedentary individuals (12%), elderly (9%), children (5%), untrained post-menopausal women (3%), and construction workers or untrained premenopausal women (2%).

Modes of training: among the included articles, the following 20 modes of training were utilized (some studies had more than one mode of training): strength training (49%), plyometric training (27%), endurance training (9%), speed training (7%), vibration training (6%), Olympic weightlifting (4%), balance (3%), flexibility (3%), injury prevention program (3%), soccer (2%), agility (1%), calisthenics (1%), capoeira (1%), coordination (1%), physical education classes (1%), powerlifting (1%), softball (1%), swimming (1%), and wrestling (1%). The sport-specific training of the athlete was combined with experimental intervention/training in 58% of the articles. The duration of training varied from 3 weeks[65,82,98,111,149,170] to 156 weeks[126] with a pooled sample mean of 13 ± 15 weeks.

Countermovement jump performance variables: a total of 63 CMJ variables were utilized in the studies. However, there was a paucity of literature quantifying 73% of the variables (i.e., only one or two articles). Furthermore, 35% of all variables had a CV (95% CI) greater than 30% (i.e., large) (Supplementary material Table SM1). The CMJ height and peak power were used to monitor fatigue effects (3%) and all CMJ performance variables were used to monitor supercompensation effects (100%).

Some data could not be obtained from the authors in four studies. The researchers of one article did not present mean and standard deviations for 10 of their CMJ variables (i.e., ratio of the flight time by contact time; mean impulse; height; displacement of body center of mass; peak velocity; mean force; mean power; peak force; peak power, and maximum rate of force development)[135] and two other articles did not detail CMJ height values.[74,87] Finally, in one article it was impossible to determine velocity at peak power.[72]

Thirty-five meta-analyses with four comparisons between the subgroups highest and average CMJ variables were performed. The sensitivity of each variable to detect change was determined by establishing the significance ($p < 0.05$) of the ES for each CMJ variable following fatigue and/or supercompensation conditions. The height was sensitive to fatigue [overall: ES = −0.27 (−0.48–0.05), $p = 0.01$; $I^2 = 39.8$, $p = 0.06$]; however, the highest height was not sensitive [highest: ES = −0.04 (−0.33–0.24), $p = 0.76$; $I^2 = 33.5$, $p = 0.15$]. On the other hand, the average height was sensitive to changes in fatigue [average: ES = −0.56 (−0.89–0.24), $p = 0.00$; $I^2 = 00.0$, $p = 0.50$] (Fig. 2).

CMJ's sensitivity to determining supercompensation effects was significant for a number of variables and the effects can be observed in Fig. 3, with all studies included in the Supplementary Material (SM) (Fig. SM1). The following is a summary of these results: height [overall: ES = 0.37 (0.32–0.43), $p = 0.00$; $I^2 = 25.8$, $p = 0.00$; highest: ES = 0.33 (0.27–0.38), $p = 0.00$; $I^2 = 20.0$, $p = 0.01$; average: ES = 0.74 (0.58–0.90), $p = 0.00$; $I^2 = 15.8$, $p = 0.224$]; peak power [Overall: ES = 0.46 (0.32–0.59), $p = 0.00$; $I^2 = 45.9$, $p = 0.00$; highest: ES = 0.44 (0.30–0.58), $p = 0.00$; $I^2 = 44.2$, $p = 0.00$; average: ES = 0.83 (0.19–1.47), $p = 0.011$; $I^2 = 54.1$, $p = 0.11$] (Fig. SM2); mean power [highest: ES = 0.30 (0.15–0.44), $p = 0.00$; $I^2 = 00.0$, $p = 0.92$] (Fig. SM3); peak velocity [highest: ES = 0.53 (0.17–0.89), $p = 0.00$; $I^2 = 70.1$, $p = 0.00$] (Fig. SM4); peak force [highest: ES = 0.66 (0.31–1.02), $p = 0.00$; $I^2 = 75.6$, $p = 0.00$] (Fig. SM5); mean impulse [highest: ES = 0.52 (0.00–1.04), $p = 0.05$; $I^2 = 00.0$, $p = 0.89$] (Fig. SM6); and, eccentric mean power [highest: ES = 1.01 (0.37–1.65), $p = 0.00$; $I^2 = 00.0$, $p = 0.40$] (Fig. SM7).

Another CMJ performance variable, the power (calculated by utilising jump height and body mass of the participant) was sensitive to supercompensation [overall: ES = 0.52 (0.08–0.97), $p = 0.02$; $I^2 = 15.0$, $p = 0.32$]. However, in the subgroup analysis, the highest power was not sensitive [highest: ES = −0.04 (−0.78–0.71), $p = 0.92$; $I^2 = 00.0$, $p = 0.86$] but the average power was sensitive [average: ES = 0.83 (0.28–1.38), $p = 0.00$; $I^2 = 00.0$, $p = 0.74$] (Fig. SM8).

The sensitivity of twenty-four CMJ variables were inadequate in determining supercompensation effects; eccentric displacement of body center of mass (Fig. SM9), maximum rate of force development (Fig. SM10), mean force (Fig. SM11), force at peak power (Fig. SM12), duration of concentric phase (Fig. SM13), velocity at peak power (Fig. SM14), peak negative velocity (Fig. SM15), displacement of body center of mass (Fig. SM16), peak acceleration (Fig. SM17), work (Fig. SM18), height with 20 kg (Fig. SM19), contact time (Fig. SM20), duration of eccentric phase (Fig. SM21), height with 40 kg (Fig. SM22), time to peak force (Fig. SM23), rate of power development (Fig. SM24), ratio of the velocity of take off by peak upward velocity (Fig. SM25), ratio of the velocity of take off by maximum velocity (Fig. SM26), ratio of the duration of concentric phase by duration from minimum vertical force to take off (Fig. SM27), jump efficiency (Fig. SM28), Esslinger fitness index (Fig. SM29), peak power with 50 kg (Fig. SM30), force at transition (Fig. SM31), and duration from minimum vertical force to take off (Fig. SM32). Thirty-two of the sixty-three CMJ performance variables were reported in a single study (Table SM2). Six of these dependent variables (i.e., height with 30 kg; area under the force-velocity loop; eccentric rate of force development; time between peak power and peak displacement; peak power with 40 kg; and peak velocity with 40 kg) were sensitive to detecting supercompensation effects. In summary, the number of variables sensitive in determining supercompensation was 22% (8 + 6 = 14, i.e., 22%) whereas 78% of the CMJ variables were not sensitive enough to determine fatigue or supercompensation effects (total of non-sensitive: 25 + 24 = 49, i.e., 78%).

4. Discussion

Monitoring neuromuscular status was aligned to the ability of the CMJ to detect the effects of fatigue and supercompensation on performance. The main objective of this meta-analysis therefore was to determine the efficacy of using averaged or highest CMJ performance in monitoring this status. The secondary aim

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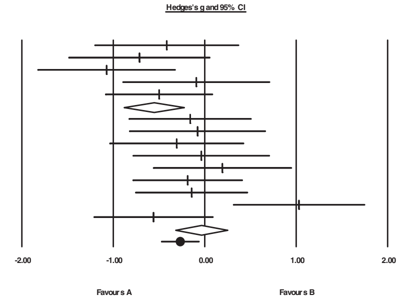
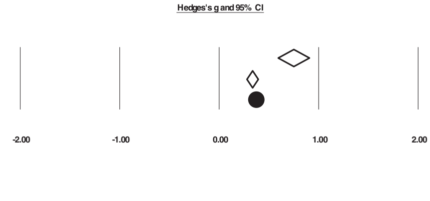
Group by Group	Study name (First Author)	Training/Intervention	Sport/Sample	Duration (weeks)	Sig. (Y/N)	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Average	2008 Bazett-Jones [181]	Stg	Track and Field	6	N	-0.42	0.41	0.17	-1.21	0.38	-1.02	0.31	16.99
Average	2012 Theanthong [195]	Ply + Jog + Stg	Soccer	6	Y	-0.71	0.40	0.16	-1.49	0.07	-1.79	0.07	17.69
Average	2012 Theanthong [195]	Ply + Stg	Soccer	6	Y	-1.07	0.39	0.15	-1.83	-0.31	-2.77	0.01	18.60
Average	2012 Theanthong [195]	Ply + Wat	Soccer	6	N	-0.09	0.41	0.17	-0.91	0.72	-0.22	0.82	16.30
Average	2013 Mohr [199]	Spo-Esp (Competitive Period)a	Soccer	6	Y	-0.50	0.30	0.09	-1.09	0.10	-1.65	0.10	30.42
Average						-0.56	0.17	0.03	-0.89	-0.24	-3.37	0.00	
Highest	2009 Chaouachi [73]	Spo-Esp (during Rif)	Judo	7	N	-0.16	0.35	0.12	-0.84	0.52	-0.46	0.64	11.53
Highest	2011 Memari [129]	Spo-Esp (during Rif)	Teakwondo	7	N	-0.08	0.38	0.15	-0.83	0.67	-0.21	0.84	10.01
Highest	2013 Aloui [52]	Spo-Esp (during Rif; 5pm)	Soccer	5	Y	-0.31	0.38	0.14	-1.05	0.43	-0.81	0.42	10.21
Highest	2013 Aloui [52]	Spo-Esp (during Rif; 7am)	Soccer	5	N	-0.04	0.38	0.15	-0.79	0.72	-0.10	0.92	9.97
Highest	2013 Aloui [53]	Spo-Esp (during Rif)	Judo	6	Y	0.19	0.39	0.15	-0.57	0.96	0.49	0.62	9.77
Highest	2013 Mohr [199]	Spo-Esp (Competitive Period)h	Soccer	6	N	-0.19	0.31	0.10	-0.79	0.42	-0.61	0.55	13.24
Highest	2014 Arcos [57]	Spo-Esp (Competitive Period)	Soccer	9	N	-0.14	0.32	0.10	-0.77	0.48	-0.45	0.65	12.85
Highest	2014 Rollo [150]	Spo-Esp (Competitive Period; 1 game per week)	Soccer	6	N	1.03	0.37	0.14	0.30	1.76	2.78	0.01	10.49
Highest	2014 Rollo [150]	Spo-Esp (Competitive Period; 2 games per week)	Soccer	6	Y	-0.56	0.34	0.11	-1.22	0.10	-1.66	0.10	11.93
Highest						-0.04	0.15	0.02	-0.33	0.24	-0.31	0.76	
Overall						-0.27	0.11	0.01	-0.48	-0.05	-2.44	0.01	



Meta Analysis

Fig. 2. Fatigue; CMJ height (highest and average).
Sig. = significant difference; Y = yes; N = no; Stg = stretching; Ply = plyometric training; Jog = jogging; Wat = water; Spo-Esp = sport-specific training mode; Rif = Ramadan intermittent fasting.

Group by Group	Study name (First Author)	Training/Intervention	Sport/Sample	Duration (weeks)	Sig. (Y/N)	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Average						0.74	0.08	0.01	0.58	0.90	9.21	0.00	
Highest						0.33	0.03	0.00	0.27	0.38	11.15	0.00	
Overall						0.37	0.03	0.00	0.32	0.43	13.63	0.00	



Meta Analysis

Fig. 3. Supercompensation; height (highest and average).

was to determine the sensitivity of the dependent variables to detect changes in CMJ performance. The concept of neuromuscular status adopted in this study, using CMJ performance to monitor fatigue and/or supercompensation effects, has been used by previous researchers.[8,9,200,201] Based on our results, the average CMJ height was more sensitive than highest CMJ height in monitoring the effects of fatigue and supercompensation on performance. All comparisons between highest and average CMJ performance, found the average values more sensitive than the highest values in monitoring neuromuscular status. In addition, the following CMJ performance variables were also deemed appropriate to assess supercompensation effects following a training intervention: peak power, mean power, peak velocity, peak force, mean impulse, and power calculated by equation. The main analysis revealed that when CMJ variables were averaged across all performed trials, the variables sensitivity to detect performance changes were enhanced in comparison to reporting the highest value. This indicates that the odds of finding the true score are increased when the average value is used to track changes in CMJ performance.

The oldest article cited by researchers dates back to 1966, where the authors stated that the "the best of three trials was recorded" in their CMJ procedures.[202] In 1973, the overarching question was raised: should experimenters utilize the best (peak) or average scores in the measurement of physical performance?[30] The author described the benefits of using the average, but also gave the option of using the highest score in case the researcher needed to ensure that measurement error was small relative to within-individual variation. This suggestion has been followed since then, so that a classical reference cited from 1987 gave both options (i.e., highest or average).[203] Recently, the question to report the best/highest score or average across a number of trials has been raised again.[29] The researchers found no-significant differences between highest [ES = 0.32 (0.05–0.65)] and average [ES = 0.35 (0.02–0.62)] CMJ height and concluded that using either the highest or average CMJ had a similar ability to monitor changes in CMJ performance. However, when data was pooled to increase the sample size for the current meta-analysis, differences between the highest score and averaged score were evident.

The majority of the interventions were conducted on individual and team sport athletes (i.e., 61%) as the CMJ has been identified as a simple, effective, and popular performance monitoring test.[6] Additionally with regards to the sport-specific training mode effects, CMJ performance has been used to monitor the effects of strength, plyometric, endurance, and speed training. These training methods are normally used to improve the basic fitness characteristics of athletes,[31] and the efficacy of these interventions is generally quantified via assessment of CMJ performance. CMJ performance changes in response to these modes of training are well described in the literature and they have been documented in some meta-analyses and systematic reviews.[204–210]

Among the 63 dependent variables used to monitor adaptations in CMJ performance, the efficacy and validity of 73% of these variables require further investigation due to insufficient sample sizes. The reduced number of studies may influence either the magnitude of the ES or of the CV. Thus, 78% of the dependent variables were found to have non-significant ES with 35% of those variables having a large CV and as such, the utility of these variables would seem problematic in the tracking of neuromuscular status. That is, a large CV makes it increasingly difficult to detect statistical differences between moments (e.g., pre, mid, post) and intervention groups, unless these differences are also very large.[51] For example, eccentric mean power had a large CV and ES; therefore, its utilization in neuromuscular tracking should proceed with caution.

Conversely, nine variables were found sensitive in the tracking of supercompensation effects. Of note was peak velocity with a small CV and moderate ES, though, it had moderate and significant heterogeneity, however, peak velocity was used in the highest jump only.[17,107,115,126,136,139,140,154,167,168,173] According to the results of this meta-analysis, if the average jump was used, it could increase the ES and reduce heterogeneity of peak velocity. On the other hand, kinematic parameters, such as peak velocity, have been assessed within the field;[211] however, the use of accelerometers (as an alternative measurement) was not recommended.[212] Other possible equipment, the linear position transducer (LPT) has been suggested for field and laboratory assessments,[213,214] but to the best of the authors' knowledge, the LPT also should not be utilised, because most studies have not detailed the reliability and validity of peak velocity.[215–217] Therefore, peak velocity should be measured with the force plate. Furthermore, the use of force plate to calculate peak velocity and CMJ height leads us to the similarity between these variables. When the CMJ height is calculated using impulse with the equation height = $v^2/2g$, where g is the acceleration due to gravity and v is the vertical takeoff velocity, this v should be the peak velocity. Consequently, one of these variables (i.e., peak velocity or CMJ height) is recommended for coaches and sport scientists to choose. The CMJ height had moderate CVs and moderate sensitivity to supercompensation effects with similar results to peak power. Another advantage of CMJ height is it's simplicity, as it can be calculated from flight time data obtained from a force plate or contact mat, whereas other variables require the force plate. Mean power, mean impulse, and peak force had moderate CVs and moderate sensitivity. In addition, the comparison among the power calculated by equation subgroups, only the averages were sensitive in detecting supercompensation effects ($p < 0.05$). Using the highest subgroup resulted in a moderate CV and small ES, while the average subgroup had a moderate CV and a large ES.

It would seem from the overall analysis that publication bias had no significant impact on the results. However, the split analysis revealed a large difference between the highest and average groups. This result is corroborated by the results of the meta-analysis, where greater ES were associated with the average CMJ variables. Therefore, it is thought averaged values are better measures to be used in the assessment of fatigue and/or supercompensation (i.e., monitoring of the training process). This can be rationalized by understanding concepts around Type II error, where a small sample size can increase the odds of not finding significant differences when they actually exist.[218] In this case, the small sample size is the trial size (i.e., the highest CMJ) used to determine the change in the dependent variable of the study. Researchers have verified the negative effect of the reduced trial size on statistical power.[219,220] Thus, the average of several repetitions provides a more stable and representative value[221,222] and less prone to Type II error.[218] Using averaged values is typically utilized for biomechanical parameters[223,224] and it has been suggested relevant for physiological parameters as well.[225,226] Based on current findings, we were unable to determine if there are differences in CMJ variable sensitivity related to the number of CMJ trials that were averaged. However, the number of repetitions to be used as an average for CMJ height have been calculated based on the CV and 6,[22] 8,[227] and 12 jumps[228] have been suggested as optimal for CMJ analysis.

This review of CMJ performance has used a meta-analytical approach to determine and justify why the utilization of average values are more sensitive than the highest values in detecting change. However, psychological, physiological, and biomechanical factors also play an important role in CMJ performance in terms of biological variability. The psychological effect of immediate knowledge of results during multiple trials contributes to the reliability of measurements.[229,230] Other influential factors may include; (i) changes in the muscle excitation-contraction coupling process,[231] and (ii) musculoskeletal redundancy, which is defined as fluctuations in individual muscle activity during force production causing variability in muscle activation patterns.[232] Therefore, the natural variability of performance during human movement could be well addressed when the average approach is used to monitor neuromuscular status.

The exclusion of acute studies (<3 weeks in duration) may have influenced the results. Acute studies were excluded in an attempt to minimize the confounding factors of training interventions (short- and long-term); however, the durations of the included interventions varied considerably and should be taken into consideration when interpreting the results. Of note, a number of acute interventions have found CMJ force-time variables to be sensitive in detecting acute changes in CMJ performance.[3,21,22] Other factors that may have confounded the results include the pooling of data across studies with a range of population types (sport, ability, and training status) and the inclusion of all devices to measure CMJ performance (e.g., force plates, position transducers, and contact mats).

5. Conclusions

Firstly, the vast majority of studies have used the highest CMJ performance for analysis; however, when the comparison between highest and average results was possible, the averaged jump results were more sensitive than the highest jump in detecting fatigue or supercompensation effects. Furthermore, a reduced number of studies have used the CMJ performance for monitoring fatigue effects. From the meta-analysis it can be concluded that the averaged CMJ height would seem the most appropriate variable to monitor neuromuscular status when compared to the highest CMJ height. Additionally, peak power, mean power, peak velocity, peak force, mean impulse, and calculated power would seem merit worthy in quantifying supercompensation effects. Utilizing the average CMJ, of all repetitions performed, for all these variables should increase their sensitivity to track fatigue during the training process. Further research is needed to establish the sensitivity of other CMJ variables to detect fatigue effects.

Practical applications

Given the findings of this meta-analysis the following practical applications are recommended:

- Averaged CMJ performance without arm swing should be used to track neuromuscular status.
- Average CMJ height was more sensitive than highest CMJ height to monitor changes in neuromuscular status.
- Variables used to monitor neuromuscular status should have a small-moderate CV and a moderate-large ES.
- For other testing (e.g., sprint testing) it is recommended that average values be used to monitor training effects.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jsams.2016.08.011.

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