SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

VOLUME
2

ISSUE
3

July 2023

EDITED & PUBLISHED BY

ARD
ASOCIACIÓN ESPAÑOLA

ASOCIACIÓN ESPAÑOLA DE ANÁLISIS DEL RENDIMIENTO DEPORTIVO

SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

REVIEW ARTICLE

A meta-analytic comparison of the effects of consuming carbohydrate with and without protein on postexercise plasma insulin and glucagon responses in healthy, trained males

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ABSTRACT

This meta-analysis evaluates how hydrolysed protein and carbohydrate (CHO) mixtures compare with intact protein and CHO mixtures regarding post-exercise plasma insulin and glucagon responses in healthy endurance trained males. Studies measuring insulin and/or glucagon following an exercise bout with ingestion of CHO vs. CHO+ protein were included. Random-effects meta-analyses were conducted on the insulin peaks over time. Overall, 33 trials from 20 articles were included. The ingestion of CHO+ protein induced significantly higher insulin peaks than ingestion of CHO only from 30 to 240 minutes postexercise (30-180 min: $p < .001$, 210-240 min: $p < .01$), higher insulin area under the curve ($p < .001$), and greater muscle FSR ($p < .001$). No statistically significant differences on insulin peaks over time were found between the ingestion of CHO+ intact protein and CHO+ hydrolysed protein or differences in muscle glycogen synthesis rate or glycogen peaks. Findings provide evidence the co-ingestion of CHO+ protein is a better strategy for recovery for endurance-type male athletes than the ingestion of CHO only. However, more research is warranted to understand whether there are differences between the ingestion of intact protein and its hydrolysed counterpart with CHO, and the impact on glucagon responses.
Keywords: Plasma glucose; Muscle FSR; Muscle glycogen synthesis; Sports nutrition.

Cite this article as:
Kuo, T-Y., Barnes, J. L., Laurson, K., & Russell, L. (2023). A meta-analytic comparison of the effects of consuming carbohydrate with and without protein on postexercise plasma insulin and glucagon responses in healthy, trained males. *Scientific Journal of Sport and Performance*, *2*(3), 256-271. https://doi.org/10.55860/XVLL6808

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Submitted for publication January 02, 2023.
Accepted for publication April 10, 2023.
Published April 18, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/XVLL6808

INTRODUCTION

Muscle glycogen is the most important fuel source during moderate- to high-intensity exercise, the amount of which can decrease rapidly during prolonged endurance-type exercise or high-intensity exercise of relatively short duration (Burke, 2004; van Loon *et al.*, 2000; Ivy *et al.*, 2003; Jentjens *et al.*, 2003; Kaastra *et al.*, 2006). Carbohydrate (CHO) ingestion plays a decisive factor of the rate of muscle glycogen synthesis (Burke *et al.*, 1993; Burke *et al.*, 2004; Costill *et al.*, 1981), and can inhibit muscle protein breakdown to further spare muscle protein from consumption after exercise (Beelen *et al.*, 2008; Børsheim *et al.*, 2004). Therefore, it is essential to ingest adequate amount of CHO to optimize glycogen synthesis rates after exercise (Ivy *et al.*, 1988a). However, how different factors, such as the type of CHO and administration frequency, moderate the muscle glycogen repletion rate remains unclear.

Previous studies discovered that co-ingestion of small amounts of protein and/or amino acids (AAs) with CHO may further accelerate muscle glycogen repletion and reduce muscle damage by increasing net muscle protein availability (Koopman *et al.*, 2005; Miller *et al.*, 2003; Van Loon *et al.*, 2000b; Hausswirth *et al.*, 2011). This is considered to be led by the synergistic effect of the ingestion of carbohydrate and protein mixtures, which promotes a greater insulin response (Nuttall et al., 1984; van Loon et al., 2000b). Such increase in insulin responses has been suggested to accelerate plasma glucose metabolism and thus increase the efficiency of glycogen repletion by increasing the activity of glycogen synthase (Bak *et al.*, 1991; Ivy *et al.*, 1998). Specifically, Kaastra (2006) found that co-ingestion of a casein protein hydrolysate (0.4 $g \cdot kg^{-1} \cdot h^{-1}$) with CHO (0.8 $g \cdot kg^{-1} \cdot h^{-1}$) induced a more than two-fold insulin response compared to CHO ingestion alone during postexercise recovery in endurance-trained cyclists. The insulin response could be further stimulated by the addition of free leucine. Hence, it is generally recommended to ingest both CHO and protein for postexercise recovery. However, the exact amount and type of protein source and the desired timing for protein administration are still under considerable debate.

Another potential aspect of protein ingestion is that protein may play an important role in weight management, although no meta-analyses or reviews have been conducted to address this question. Studies have shown that protein induces a higher thermic effect of food (TEF) (Calcagno *et al.*, 2019). Although TEF accounts for only 10% of total energy expenditure (TEE), having protein in the diet has been demonstrated to be a feasible long-term strategy for weight management (Calcagno et al., 2019). Furthermore, TEF may contribute to a higher percentage of TEE in subjects with higher aerobic capacity (Hill *et al.*, 1984). In other words, this dietary strategy may be more effective for endurance-type athletes such as cyclists or marathon runners.

A reasonable explanation to the protein-induced TEF is that the glucagon concentrations will increase with the elevated plasma AA levels after protein ingestion (Farnfield *et al.,* 2009; Gannon *et al.,* 2010; Ohneda *et al.,* 1968; Unger *et al.*, 1969; van Loon *et al.*, 2000a) in order to metabolize hepatic AA (Holst *et al.,* 2017). Insulin and glucagon have to interact synergistically to promote plasma AA clearance and postprandial AA disposal (Ang *et al.*, 2019). Meanwhile, protein-induced hyperglucagonemia can effectively prevent a decline in blood glucose concentration secondary to aminogenic insulin secretion during CHO-free protein meals (Ohneda *et al.*, 1968; Unger *et al.*, 1969). Therefore, glucagon secretion should be expected for the maintenance of normal plasma glucose levels (i.e., euglycemia) following protein or AA ingestion. More importantly, by measuring the glucagon responses after protein ingestion, it is possible to understand how different types of proteins could be helpful for weight management in endurance-typed athletes.

It is worth noting that proteins can be further categorized into intact and hydrolysed protein, also named protein hydrolysate. Protein hydrolysate contains mostly di- and tripeptides, and is suggested to be absorbed more rapidly than free AA and intact proteins, which may lead to a faster increase in plasma AA (Claessens *et al.*, 2008; Koopman *et al.*, 2009; Manninen *et al.*, 2004). Protein hydrolysate has gained success and been widely used for patients with gastrointestinal tract disorder as a great protein source due to this higher digestibility than normal intact proteins (Potier *et al*., 2008). However, such advantage seems inconspicuous in healthy individuals. Few studies have addressed to whether there are meaningful differences between the ingestion of intact protein and its hydrolysed counterpart for healthy individuals.

Objectives

The aim of the present study included two interests: 1) to evaluate whether there is a difference between the ingestion of protein with CHO and the ingestion of CHO alone; and 2) to conduct a meta-analysis to evaluate how hydrolysed protein with CHO mixtures compare with intact protein with CHO mixtures in regards to post-exercise plasma insulin and glucagon responses in healthy endurance trained male subjects. Plasma insulin responses were used as a measurement of postexercise recovery quality due to a positive correlation between insulin responses and muscle glycogen repletion and protein synthesis, and glucagon responses were used to examine the potential influences of protein ingestion on weight management. The primary outcomes evaluated were the insulin peaks over time and area under curve (AUC), and glucagon peaks over time. Other secondary outcomes included muscle glycogen storage, glycogen synthesis rate, muscle fractional synthesis rate (FSR), and plasma glucose peaks over time.

METHODS

Eligibility criteria

Studies published before August 2021 were reviewed. Eligible studies were English-language reports of insulin and/or glucagon response after post-exercise interventions conducted with healthy trained male subjects. Only peer reviewed, randomized controlled trials (RCTs) were included. Studies had to have been conducted with healthy trained male subjects aged 18-65. Since the definition of a trained individual is not consistent among different articles, for the purpose of this meta-analysis, anytime authors described their sample as trained, or included professional or college-level athletes, they were considered trained individuals. If a sample was only described as healthy adults or subjects, or as adults who were obese or insulin-resistant, they were excluded. The supplementation type was liquid only, and the control trial was the ingestion of CHO alone. No restrictions on the concentration and frequency of each macronutrient intake were made. All units were integrated to be effectively measured and compared.

Study selection

Studies for potential inclusion were found by searching the following electronic databases: PubMed, Google scholar, Cochrane, and MDPI. Two search strategies were employed. Information sources included electronic databases and author searches. Search terms included protein*, insulin*, glucagon*, and athlete terms (athlete*, trained*). The star symbol (*) was used to capture derivatives (by suffixation) of the search terms. Computerized author searches were completed for corresponding authors of eligible studies.

A staged eligibility determination process was used to identify eligible studies for this meta-analysis in order to ensure all eligible studies for any part of the parent project reached the coding phase. First, title and abstracts were reviewed for visual heralds suggesting a potentially eligible study. Second, full reports were examined to determine whether the study included a post-exercise (usually involved cycling until depletion) protein intervention in healthy male participants. Third, potential primary studies were examined for any eligible primary outcomes for the parent study. Fourth, potential primary studies were evaluated to calculate insulin and glucagon response over time and AUC to identify the optimal type of post-exercise protein mixture.

Finally, studies that included secondary outcomes were evaluated to compare with the results of primary outcomes.

Data collection process

Data was extracted from studies by the lead author, with oversight second author. Raw data was mainly obtained from the research articles. For eligible studies without complete data presented in tables/narratives, the corresponding author was contacted via e-mail or the data was extracted from graphs using WebPlotDigitizer (Rohatgi, 2020). All included papers were subject to an assessment of risk of bias based on guidelines outlined by the Cochrane Handbook for Systematic Reviews of Interventions (Cochrane Collaboration, 2007). To assess for risk of publication bias, study sample size and effect sizes were evaluated using a funnel plot (Borenstein *et al.*, 2009).

Statistical analysis

A random-effects mean-comparison meta-analysis was conducted to assess if differences exist on the post-exercise insulin and glucagon responses by the ingestion of protein with CHO as compared to the ingestion of CHO alone across the studies retrieved in RStudio. As part of analyses, an overall effect size and confidence intervals were calculated in order to determine how the post-exercise insulin and glucagon responses varies across independent variables in the studies retrieved. The missing standard deviations (SD) in any trials were replaced by the average score of all the available SDs at the indicated time. Data analyses were conducted using RStudio 2021.09.0 build 351.

RESULTS

Overview of included studies

Overall, 286 potential articles were identified, of which 28 articles were duplicated. After excluding the duplicated articles, 258 were screened, and all abstracts were reviewed. Initial review resulted in 194 articles excluded, and the remaining 63 articles were reviewed. A total of 44 studies were finally excluded because their study design did not meet with the eligibility criteria of this study, such as female participants (or inability to distinguish findings by participant sex), before and/or during exercise supplementation, supplements containing lipids, untrained participants, or not reporting on the outcomes of interest. Ultimately, 33 trials derived from 20 articles were included in this meta-analysis (Table 1) with 32 trials reporting insulin peaks over time and subgroup analyses, 9 insulin AUC, 9 muscle FSR, 30 trials were included for plasma glucose peaks over time, 6 with muscle glycogen synthesis rate, 8 for muscle glycogen storage, and 5 trials were included for plasma glucagon peaks over time. No publication reported glucagon AUC (Figure 1).

Plasma insulin peaks over time

The included trials reported insulin peaks from 30 to 240 minutes, respectively. The insulin data of 3 trials (Churchward-Venne et al., 2020) at 40 minutes were used as and compared with other 30-minute data. In order to make all data consistent in having only one peak over the testing periods, the data of 2 trials (Cogan *et al.*, 2018) were streamlined, and only the data from the first two hours during recovery were utilized. The results indicated that ingestion of protein/and AA with CHO induced significantly higher insulin responses than the ingestion of CHO alone (from 30 - 180 min: $p < .001$; $I^2 = 82.88\%$ - 88.78%; from 210 - 240 min: $p < .01$; $I^2 = 71.16\%$ - 86.89%; $SMD_{30\ min} = 1.7379$, $SMD_{60\ min} = 1.6611$, $SMD_{90\ min} = 1.54$, $SMD_{120\ min} = 1.54$, $SMD_{150\ min} = 2.00$, $SMD_{180\ min} = 1.34$, $SMD_{210\ min} = 1.25$, $SMD_{240\ min} = 0.81$). The most representative results were insulin peaks at 60 minutes, which included all 32 trials (the standard mean difference was 1.6611, 95% CI 1.1864–2.1357, $p < .001$; $I^2 = 84.18\%$) (Figure 2).

Table 1. Characteristics of all included trials.

Author	Year	Age (yr.)	Weight (kg)	Hydro	Protein Type	Protein (g·kg-1·h-1)	AA Type(s)	AA Ratio	AA (g·kg-1·h-1)	CHO Type	CHO Ratio	CHO (g·kg-1·h-1)
Zawadzki	1992	-	73.1 ± 3.1	No	Milk	0.28			0	Glucose/ Maltodextrin	-	0.77
van Loon	2000	24 ± 0.6	70 ± 0.1	Yes	Wheat	0.2			0	Glucose/ Maltodextrin	4:6	1.2
	2000	24 ± 0.6	70 ± 0.1	Yes	Wheat	0.4			0	Glucose/ Maltodextrin	4:6	1.2
	2000	24 ± 0.6	70 ± 0.1	Yes	Wheat	0.1	Leu/ Phe	1:1	0.05 (Each)	Glucose/ Maltodextrin	4:6	1.2
	2000	24 ± 0.6	70 ± 0.1	Yes	Wheat	0.2	Leu/ Phe	1:1	0.1 (Each)	Glucose/ Maltodextrin	4:6	1.2
van Loon-2	2000	24 ± 0.6	70 ± 0.1	Yes	Wheat	0.2	Leu/ Phe	1:1	0.1 (Each)	Glucose/ Maltodextrin	1:1	0.8
van Hall	2000	25 ± 3	72 ± 3	Yes	Wheat	0.3			0	Glucose	1	0.8
	2000	25 ± 3	72 ± 3	Yes	Whey	0.3			0	Glucose	1	0.8
van Hall-2	2000	26 ± 2	74 ± 2	Yes	Whey	0.3			0	Sucrose	1	1
Jentjens	2001	27.1 ± 2.6	69.6 ± 2.9	Yes	Wheat	0.2	Leu/ Phe	1:1	0.1 (Each)	Glucose/ Maltodextrin	1:1	1.2
Betts	2005	21 ± 1	79.6 ± 11.2	Yes	Wheat	0.2			0	Glucose/ Fructose		1.2
	2005	22 ± 0.5	83.5 ± 11.8	Yes	Wheat	0.13			0	Glucose/ Fructose	2:1	0.8
Kaastra	2006	24.3 ± 0.8	73 ± 1.8	Yes	Casein	0.4			0	Maltose/ Maltodextrin	-	0.8
	2006	24.3 ± 0.8	73 ± 1.8	Yes	Casein	0.4	Leu	1	0.1	Maltose/ Maltodextrin	-	0.8
Betts	2007	21 ± 3	72.6 ± 8.4	No	Whey	0.3			0	Sucrose	1	0.8
Howarth	2009	22 ± 1	90 ± 5	Yes	Whey	0.4			0	Maltodextrin	1	1.2
Cepero	2010	39 ± 9.8	74.4 ± 7.2	Yes	Whey	0.13			0	-	-	0.47
	2010	39 ± 9.8	74.4 ± 7.2	Yes	Casein	0.13			0	-	-	0.47
Breen	2011	29 ± 6	77.2 ± 6.5	No	Whey	0.26			0	-	-	0.66
Bagato	2014	21 ± 1.1	63 ± 3.7	No	Milk	0.2			0	Sucrose	1	0.8
Rahbek	2014	23.9 ± 0.8	78.1 ± 1.8	Yes	Whey	0.3			0	-	-	0.3
Rustad	2016	24 ± 0.4	75 ± 3	No	Whey	0.4			0	Glucose/ Maltodextrin	1:1	0.8

Table 1. Characteristics of all included trials (Cont.).

Author	Year	Age (yr.)	Weight (kg)	Hydro	Protein Type	Protein ($g \cdot kg^{-1} \cdot h^{-1}$)	AA Type(s)	AA Ratio	AA ($g \cdot kg^{-1} \cdot h^{-1}$)	CHO Type	CHO Ratio	CHO ($g \cdot kg^{-1} \cdot h^{-1}$)
Cogan	2018	28.8 ± 2.3	75 ± 2.3	No	Casein	0.16			0	Glucose/ Maltodextrin	1:1	1.04
	2018	28.8 ± 2.4	75 ± 2.3	Yes	Casein	0.16			0	Glucose/ Maltodextrin	1:1	1.04
Sollie	2018	22.9 ± 1.2	79.5 ± 3	No	Whey	0.4			0	Glucose/ Maltodextrin	1:1	0.8
Churchward-Venne	2019	23 ± 0.3	74.2 ± 1.1	No	Whey	0.27			0	Dextrose/ Maltodextrin	-	0.61
	2019	23 ± 0.3	74.2 ± 1.1	No	Casein	0.27			0	Dextrose/ Maltodextrin	-	0.61
	2019	23 ± 0.3	74.2 ± 1.1	No	Milk	0.27			0	Dextrose/ Maltodextrin	-	0.61
Dahl	2020	26.7 ± 1.7	76.4 ± 3.2	No	Whey	0.8			0	Glucose/ Maltodextrin	1:1	0.4
Churchward-Venne	2020	27 ± 1	74.9 ± 0.9	No	Milk	0.2			0	Dextrose/ Maltodextrin	-	0.6
	2020	27 ± 1	74.9 ± 0.9	No	Milk	0.4			0	Dextrose/ Maltodextrin	-	0.6
	2020	27 ± 1	74.9 ± 0.9	No	Milk	0.6			0	Dextrose/ Maltodextrin	-	0.6

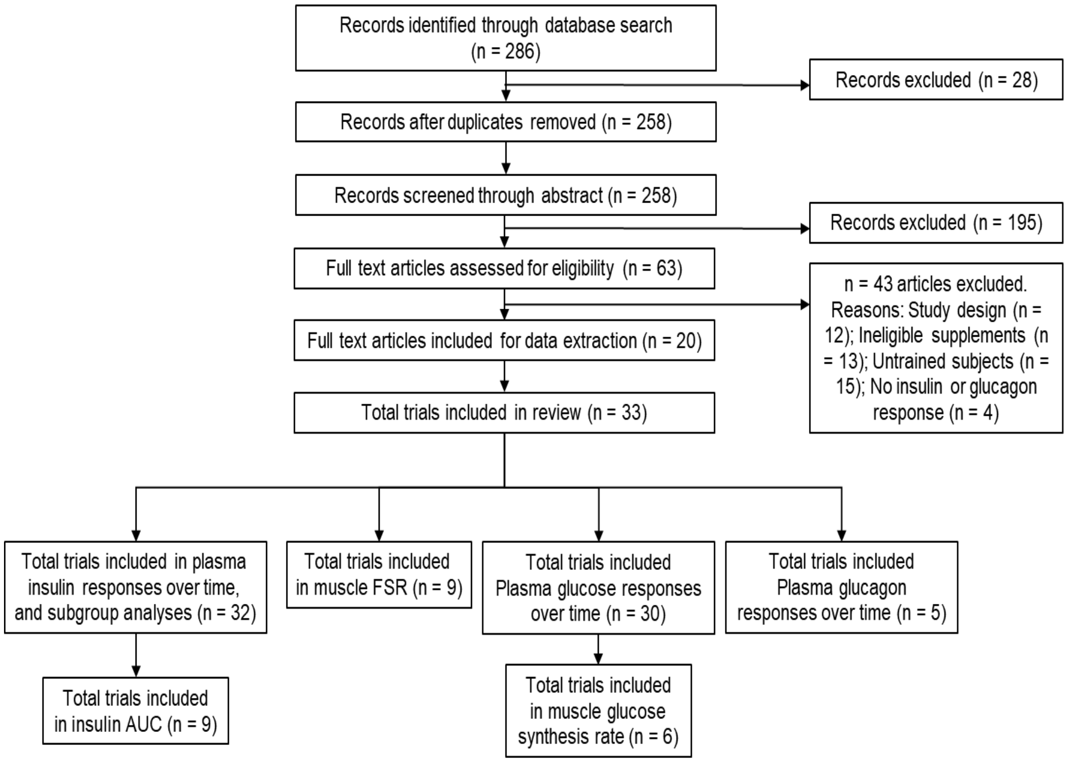
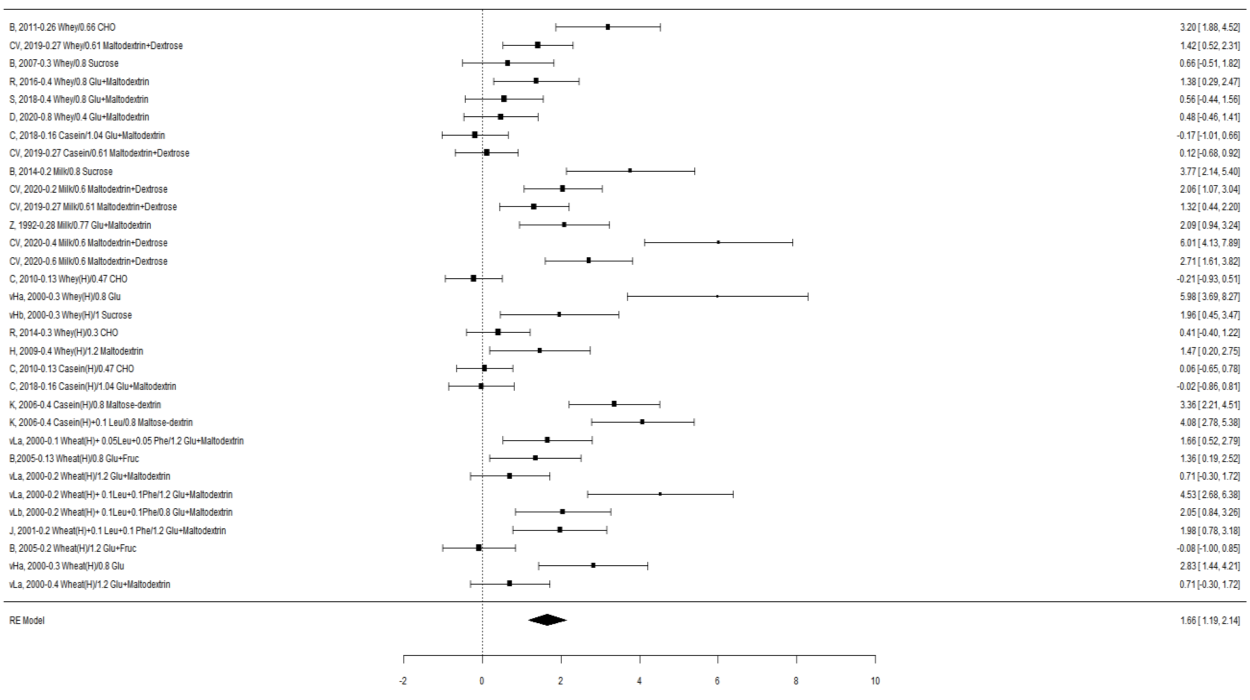


Figure 1. Flow diagram.



*Note. *Dotted lines separate the type of proteins within each group (Intact protein or hydrolysed protein). *Bolded line separates intact and hydrolysed proteins. *The data were sorted by the order: Intact or Hydrolysate > Protein types (Whey > Casein > Wheat > Milk) > Protein & Amino acid amounts.*

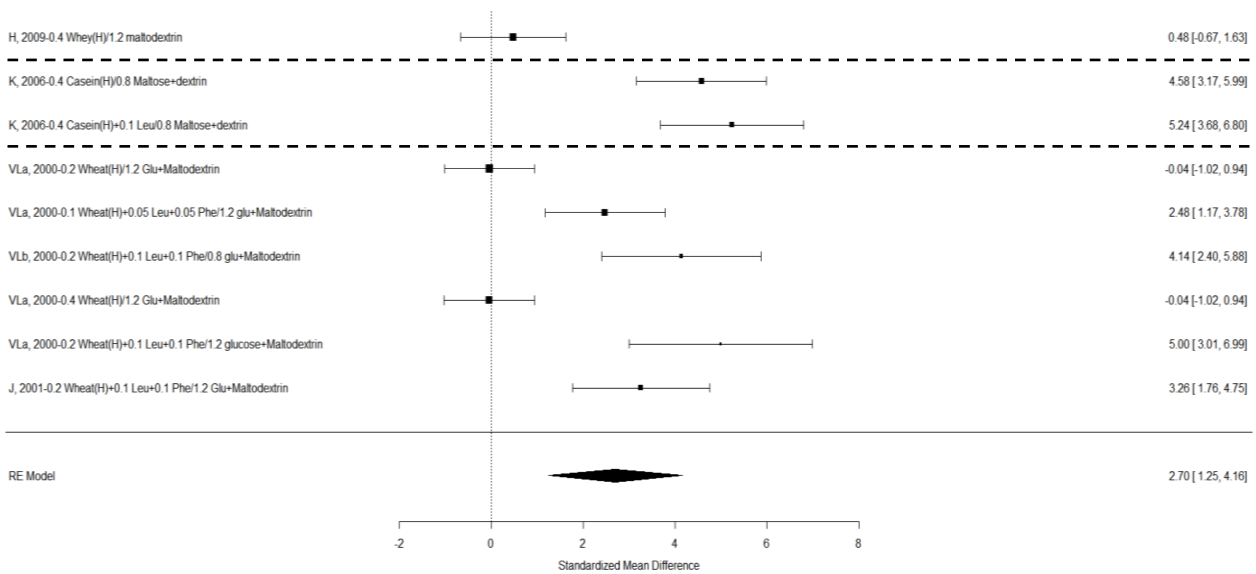
Figure 2. Insulin peaks at 60 minutes.

Plasma insulin peak subgroup tests

Subgroup analyses was applied in order to assess the difference between the ingestion of intact and hydrolysed proteins for postexercise insulin responses at 30, 60, 90, and 120 minutes. No significant difference was found on plasma insulin responses between the ingestion of intact and hydrolysed proteins (from 30 to 120 min: $\chi_{1,30}^2 = 0.08$; $\chi_{1,60}^2 = 0.01$; $\chi_{1,90}^2 = 0.01$; $\chi_{1,120}^2 = 2.71$; $df_{30\text{-}120} = 1$, $p_{30} = .77$, $p_{60} = .94$, $p_{90} = .4$, $p_{120} = .1$, $p_{30\text{-}120} > .05$).

Insulin AUC

Plasma insulin AUC after the ingestion of protein hydrolysate with CHO mixture was measured in 9 trials derived from 5 publications. No intact protein was included. The result indicated that the ingestion of protein and AA with CHO induced a significantly higher overall insulin response than the ingestion of CHO alone (the standard mean difference was 2.70, 95% CI 1.25–4.16, $p < .001$; $I^2 = 90.82\%$). (Figure 3)



*Note. * Dotted lines separate the type of proteins within each group (intact protein or hydrolysed protein). *The data were sorted by the order: protein type (whey > casein > wheat > milk) > protein & AA amounts > CHO amount. Muscle Fractional Synthesis Rate (Muscle FSR).*

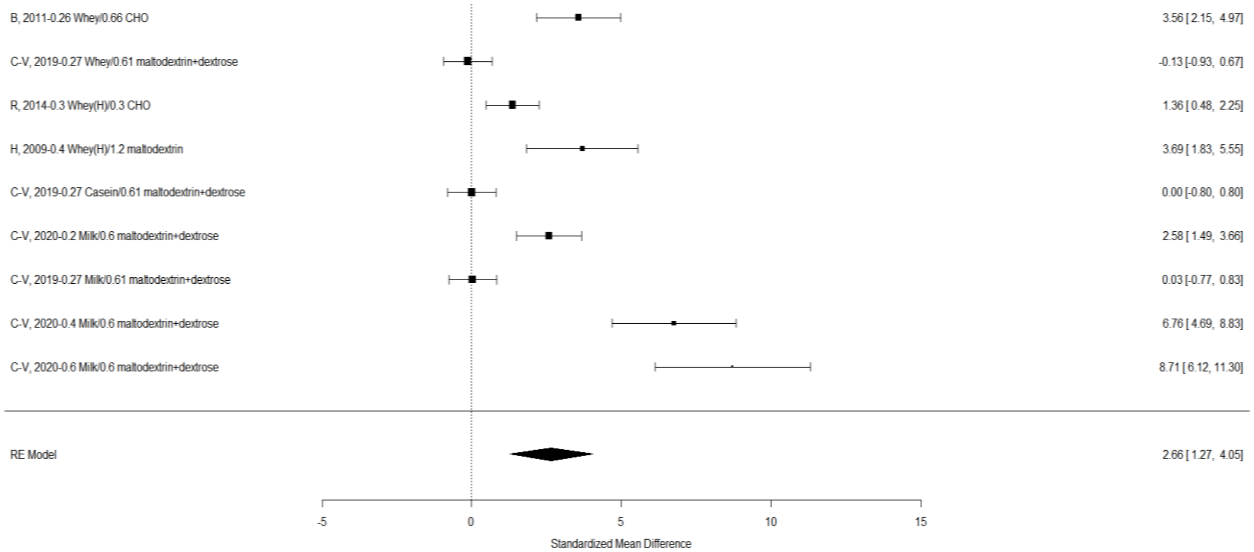
Figure 3. Forest plot: Insulin Area Under Curve (AUC).

Muscle Fractional Synthesis Rate (Muscle FSR)

FSR following ingestion of intact protein was measured in 9 trials derived from 5 publications. The result indicated that the ingestion of protein and AAs with CHO induced a significantly higher muscle FSR than the ingestion of CHO alone (the standard mean difference was 2.66, 95% CI 1.27–4.05, $p < .001$; $I^2 = 92.82\%$) (Figure 4).

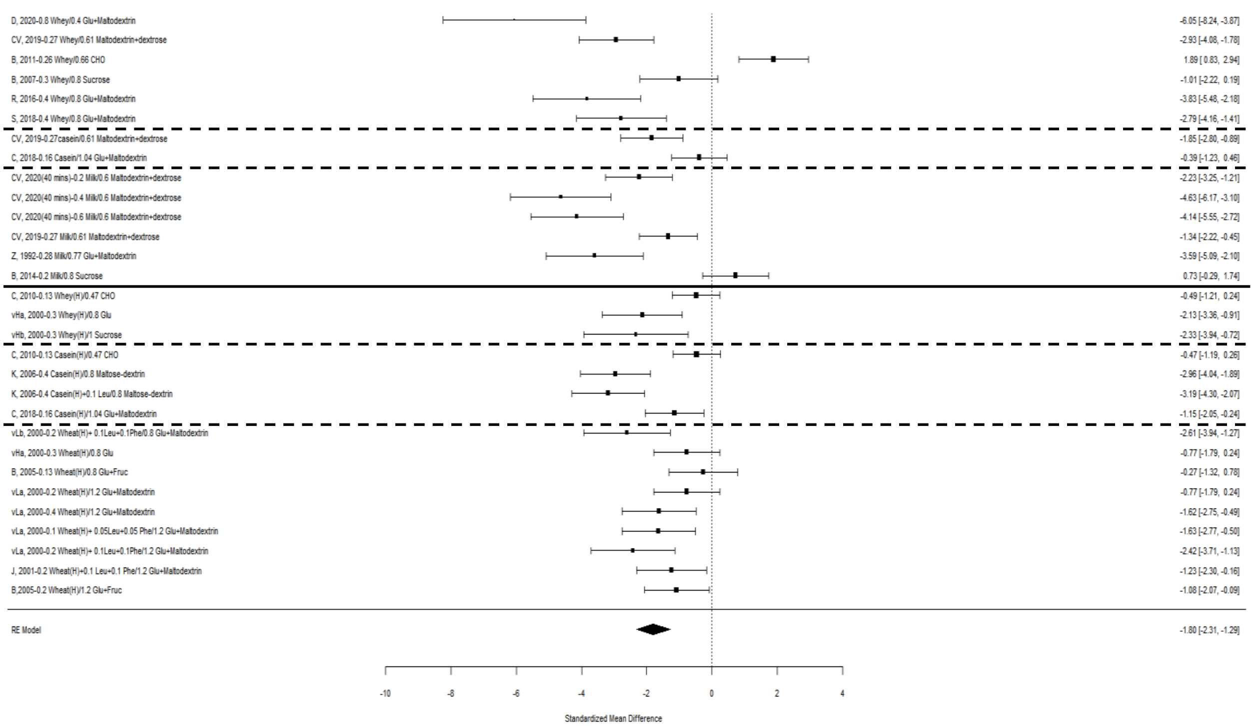
Plasma Glucose Peaks

Overall, 30 trials derived from 18 publications investigated the plasma insulin responses over time after the ingestion of intact/hydrolysed protein with CHO mixture. The glucose data of 3 trials (Churchward-Venne et al., 2020) at 40 minutes were used as and compared with other 30-minute data. In order to make all data consistent in having only one peak over the testing periods, the data of 3 trials (2 trials from Cogan *et al.*, 2018, and 1 trial was from Zawadzki *et al.*, 1992) were streamlined, and only the data from the first two hours during recovery were adopted in this study.



*Note. *The data were sorted by the order: Protein type (Whey > Casein > Wheat > Milk) > Protein & Amino acid amounts > Carbohydrate amount. Plasma Glucose Peaks Over Time.*

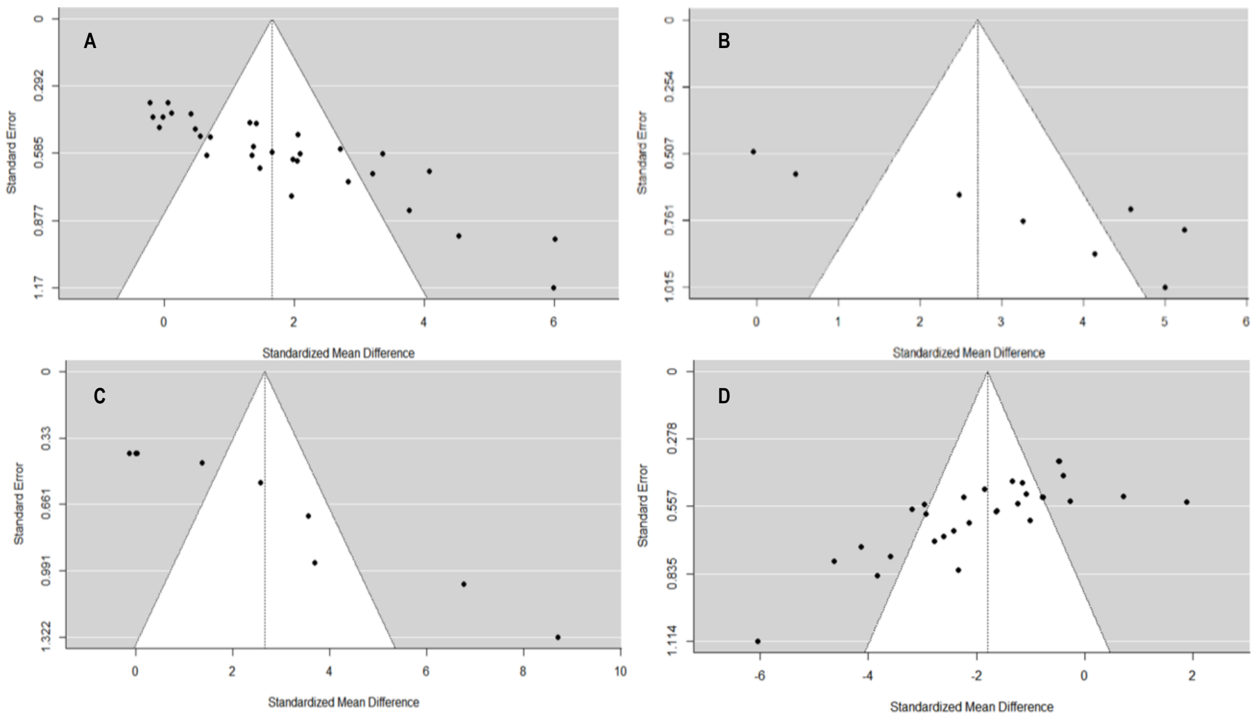
Figure 4. Muscle Fractional Synthesis Rate (Muscle FSR).



*Note. * Dotted lines separate the type of proteins within each group (Intact protein or hydrolysed protein). * Bolded line separates intact and hydrolysed proteins. *The data were sorted by the order: Intact or Hydrolysate > Protein type (Whey > Casein > Wheat > Milk) > Carbohydrate amount.*

Figure 5. Plasma glucose peaks at 60 minutes.

The results indicated that the ingestion of CHO alone induced a significantly higher plasma glucose response than the ingestion of protein/and AA with CHO (from 30 - 90 min: $p < .001$; $I^2 = 81.21\% - 87.97\%$; at 120 min: $p < .01$; $I^2 = 78.59\%$; $SMD_{30\ min} = (-1.42)$, $SMD_{60\ min} = (-1.80)$, $SMD_{90\ min} = (-1.35)$, $SMD_{120\ min} = (-0.58)$). The most representative results were glucose peaks at 60 minutes, which included all 30 trials (the standard mean difference was (-1.80), 95% CI (-2.31) - (-1.29), $p < .001$; $I^2 = 84.48\%$). (Figure 5)



Note. ***6a.*** *Funnel Plot – Insulin Peak at 60 Minutes.* ***6b.*** *Funnel Plot - Insulin Area Under Curve (AUC).* ***6c.*** *Funnel Plot - Muscle Fractional Synthesis Rate (Muscle FSR).* ***6d.*** *Funnel Plot - Plasma Glucose Peaks at 60 Minutes.*

Figure 6. Funnel plots.

Muscle glycogen synthesis rate

No significant difference on muscle glycogen synthesis rate between the ingestion of protein and AAs with CHO and CHO alone was found within the 6 trials from 5 publications (The standard mean difference was 0.82, 95% CI (-0.41)–2.05, $p > .05$; $I^2 = 85.53\%$).

Plasma glucagon peaks over time

No significant difference on plasma glucagon responses between the ingestion of protein and AAs with CHO was detected among the 5 trials derived from 4 publications (from 30 - 60 min: $p_{30} = .99$ & $p_{60} = .85 > .05$; $I^2 = 78.57\% - 84.56\%$).

DISCUSSION

The ingestion of protein with CHO was found to have significantly higher insulin responses than the ingestion of CHO alone. The analysis of insulin AUC also confirmed the same overall significantly higher insulin response by the ingestion of protein with CHO. On the other hand, the ingestion of protein with CHO does induce a significantly higher muscle FSR than the ingestion of CHO alone. Both results are in line with the conclusions made by Howarth (2009) that the ingestion of protein with CHO increased muscle FSR and improved whole body net protein balance. However, no significant difference on plasma insulin responses over time between the ingestion of intact and hydrolysed proteins was found by the heterogeneity and subgroup analysis. Of note, this lack of significant differences could be in part because of the small sample sizes in many of the included trials, the limited number of included studies, or the discrepancies in the intervals of beverage administration. It is worth noting that, in this study, hydrolysed protein with CHO produced more stable and concentrated insulin responses than intact protein with CHO, although there was no statistically significant difference in the absolute values assessed in our analyses. Furthermore, the ingestion of hydrolysed protein with CHO also shows mostly numerically higher, but not significantly different, insulin peaks after two hours (At 150 min, $SMD_{hydrolysed} = 2.11 > SMD_{intact} = 1.41$; At 180 min, $SMD_{hydrolysed} = 1.36 > SMD_{intact} = 1.29$; At 210 min, $SMD_{hydrolysed} = 1.59 > SMD_{intact} = (-0.37)$; At 240 min, $SMD_{hydrolysed} = 0.73 > SMD_{intact} = 1.01$). However, the mechanism remains incompletely elucidated. Perhaps this small difference could be influential to subsequent endurance capacity, or the advantages of ingesting protein hydrolysate would be more pronounced after resistance or high-intensity exercises, where muscle damage typically occurs (Heavens *et al*., 2014) and the AA would be in greater demand.

The plasma glucose responses of the ingestion of CHO alone were as expected and significantly higher than the ingestion of protein with CHO since the plasma glucose concentration directly reflects the overall amount of CHO intake. However, no significant difference on muscle glycogen synthesis rate was found between the ingestion of protein with CHO and CHO alone. This result is in line with the results of previous studies (Cogan *et al.*, 2018; Kaastra *et al.*, 2006; Sollie *et al.*, 2018). The possible explanation is that the increased insulin concentrations induced by the ingestion of protein with CHO may further augment glycogen synthase activity and accelerate the muscle glycogen metabolism (Kaastra *et al.*, 2006; van Loon *et al.*, 2000a; van Hall *et al.*, 2000a). Therefore, possibly due to this increased insulin response, the ingestion of protein with CHO shares a similar post-exercise muscle glycogen amount as the ingestion of CHO alone. Overall, with muscle protein synthesis stimulation being key to attenuation of exercise-induced muscle damage and muscle glycogen concentrations to be decisive in muscle fatigue (Burke *et al.*, 2004; Hausswirth *et al.*, 2011), protein with CHO should be a better strategy for short-term postexercise recovery for endurance-trained athletes or any individual who is working to maintain muscle mass after training.

Unfortunately, there was insufficient data on postexercise plasma glucagon responses with the ingestion of protein with CHO to conduct meaningful meta-analyses. This is likely due to the difficulty and imprecision in measuring *in vivo* glucagon levels. One reason is that circulating glucagon concentrations are in the low picomolar range, which is around 16-17 pmol/L (Holst *et al.*, 2019). Another reason is that many proglucagon substances also contain glucagon-like sequences and can react with reagent chemicals (Wewer Albrechtsen *et al.*, 2016). Both of which make measuring plasma glucagon concentrations more challenging. However, it is still unexpected that the included trials reported no significant difference on plasma glucagon responses between the ingestion of protein with CHO and CHO alone. More research is warranted to determine whether the protein-induced TEF is led by the glucagon response, and if such response is meaningful in long-term weight management.

Finally, the funnel plot analysis (Figure 6) revealed a trend that the studies with high standard errors (which may have been in part a function of lower sample sizes) were more likely to show stronger effects than the studies with lower standard errors. Only the funnel plots of plasma glucose responses presented an opposite trend. The asymmetry detected in these funnel plots may have been due to true heterogeneity with $I^2 > 80\%$ for most cases in this meta-analysis. Though this could also represent evidence of a publication bias for statistically significant results (Borenstein et al., 2009).

This study only included published research, which may introduce published bias. In addition, there other relevant studies published in languages such as Mandarin or French, so some relevant publications may therefore be omitted. There were also diverse units reported resulting in exclusion of some trials from analyses because of the difficulty to convert and unify the units. A limited number of publications in this field also limited the number of analyses. The inability to conduct the analysis of muscle glycogen storage and subgroup tests for glucose or muscle fractional synthesis to determine the differences between the ingestion of intact protein and its hydrolysate are examples of this case. Moreover, the limited numbers of included trials could not minimize the power of individual difference made by the subjects, which could be the reason of no significant difference of some results. On the other hand, bias may still happen due to a lack of report of standard deviations from some included trials as these missing numbers were substituted by the mean value of the sum of the existing standard deviations in this meta-analysis.

CONCLUSION

In conclusion, this meta-analysis demonstrates robust evidence in the existing peer-reviewed literature that, for trained male athletes, the ingestion of protein with CHO is a better post-exercise recover strategy than CHO alone. The varying insulin response induced by different protein ingestion implies a possibility of combined protein ingestion for different recovery purposes and training plans. In addition, it may be possible to further define postexercise food quality by using insulin and glucagon indexes once the mechanism of glucagon is further elucidated.

AUTHOR CONTRIBUTIONS

Conceptualization, T-Y. K., J. L. B., L. R.; Methodology, T-Y. K., J. L. B., K. L., L. R.; Investigation, T-Y. K., L. R.; Writing – Original draft, T-Y. K.; Writing – Review and Editing, T-Y. K., J. L. B., K. L., L. R. All authors approved the final version of this paper.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

REVIEW ARTICLE

Masters sprinters: Less is more

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ABSTRACT

Masters athletes have been considered a paradigm of successful aging, which research has shown that many of the age-associated physiological changes are more related to external factors to aging itself, such as sedentary lifestyle and deconditioning. Sprint training always poses a challenge, even more in such demanding athletes as masters sprinters, given that age mainly affects those physical capabilities that are most determinant of sprint performance, such as speed, strength, flexibility, and coordination. The main purpose of this paper was to comprehensively review masters sprinters training, emphasizing certain aspects that are especially relevant in these athletes, such as training principles, specific resistance training, recovery strategies, and invisible training.
Keywords: Sprint performance; Athletic training; Resistance training; Recovery training; Masters athlete.

Cite this article as:
Eizaga Rebollar, R., & García Palacios, M. V. (2023). Masters sprinters: Less is more. *Scientific Journal of Sport and Performance*, *2*(3), 272-288. https://doi.org/10.55860/TDFE8017

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Submitted for publication April 04, 2023.
Accepted for publication April 28, 2023.
Published May 29, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/TDFE8017

INTRODUCTION

Maximum speed is determined not so much by moving the limbs fast as by exerting force against the ground and minimum ground contact time. Therefore, sprint training should be oriented to the development of maximum power in the large muscle groups through sprint, strength and jump work.

Masters athletes are individuals over the age of 35 who follow high-level physical training programs and participate in competitions designed specifically for them. These athletes have been a model for studying the aging process and the effects of physical training on aging and have been proposed as examples of successful aging. This research has shown that many of the physiological changes associated with aging are actually attributable to factors extrinsic to aging itself, such as sedentary lifestyle and deconditioning (Geard et al., 2017; Tanaka, 2017).

The main objective of this narrative review was to review the sprint training in such a demanding athlete as the masters athlete. First, a brief commentary was made on the physiological changes associated with age that can condition performance and the appearance of injuries in the masters athlete. Subsequently, the most relevant aspects of sprint training adapted to the masters athlete were reviewed. The bibliographic search was carried out between January 2002 and December 2022, in the following search engines and databases: Google, PubMed, Embase and Cochrane Library. The search terms used were: sprint performance; athletic training; resistance training; warm-up; recovery; nutrition; masters athlete; aging.

MASTERS SPRINTER PHYSIOLOGY

Energy systems

The predominant energy system in sprinting is the anaerobic system. Within this we differentiate two systems according to the metabolic contribution: the alactic system, which provides energy from the phosphagen accumulated in the muscle cell (ATP and phosphocreatine) and has a very limited duration, between 5 and 15 seconds; and the lactic system, which provides energy from anaerobic glycolysis from 15-20 seconds and up to 45-90 seconds. Sprint training will induce enzymatic adaptations mainly in these energy systems although, to a lesser extent, it will also induce them in the aerobic system (which provides energy from aerobic glycolysis from 90 seconds).

Age-associated changes in the anaerobic system include reduced muscle levels of substrates and enzymes involved in alactic metabolism (phosphocreatine and creatine kinase) and lactic metabolism (glycogen and lactate dehydrogenase); and decreased peak blood concentrations of the main end product of anaerobic metabolism (blood lactate) and its main buffer to counteract the resulting acidosis (bicarbonate) (Reaburn & Dascombe, 2009).

Endocrine system

Age is associated with changes in hormone secretion and feedback patterns. From the third decade on, there is a generalized decrease in hormone levels, and among them, anabolic hormones—insulin, testosterone, somatotropin (GH) and somatomedin (IGF-1)—which play a fundamental role in tissue repair and adaptation to training (van den Beld et al., 2018).

Cardiovascular system

The main changes in the cardiovascular system associated with age are mostly related to the aerobic system and are the following: decrease in maximum heart rate (1 beat per year from the age of 10 years), due to the loss of cells in the cardiac conduction system and lower response to circulating catecholamines; and decrease in maximum oxygen consumption (10% per decade from the age of 25 years) due to lower muscular oxygen extraction, due to the progressive loss of muscle mass (Cheitling, 2003).

Nervous system

Dynapenia is the generalized loss of muscle strength and power associated with age (7-8% per decade from the age of 30) and is due to the changes it produces in the motor unit or complex formed by a motor neuron and the set of muscle fibres it innervates.

Within the nervous system, there is a reduction in the number, size and firing of alpha motor neurons; and a decrease in nerve transmission at the neuromuscular junction or motor plate due to denervation (without regeneration) of the motor plate (Tanaka et al., 2019).

Musculoskeletal system

At the muscular level, sarcopenia or progressive loss of muscle mass occurs from the age of 40 at a rate of 0.5-1% per year. Although it affects type I (slow twitch) and type II (fast twitch) muscle fibres, it seems to be more marked in type II fibres. Therefore, the loss of speed (0.09 m/s per year) is more evident than the loss of endurance (0.06 m/s per year). There is another phenomenon associated with age, which is sarcostenia or intrinsic weakening of the muscle and which is due to the decrease in contractile proteins (actin and myosin) and fatty infiltration of the muscle.

At the bone level, osteoporosis or progressive loss of bone mass occurs in men from the age of 50 at a rate of 0.4% per year and in women from the age of 30 at a rate of 0.75-1% per year (tripling after menopause) and may be related to pathological or stress fractures. It is worth noting the close communication between bone and muscle in such a way that they share control mechanisms and, therefore, changes in bone or muscle mass are regulated by the same factors.

At the joint level, age is associated with a decrease in collagen production which affects tendons and joints, leading to a progressive decrease in flexibility and range of joint motion. Likewise, age is associated with a decrease in the production of mucopolysaccharides which favours the accumulation of water in the cartilages and weakens them, leading to a progressive loss of cartilage and may be related to different degrees of degenerative joint disease or osteoarthritis (Tanaka et al., 2019; Wright & Perricelli, 2008).

TRAINING PRINCIPLES

Overload

Progressive increase in training load—volume and intensity—along with adequate recovery periods are associated with neuromuscular and metabolic adaptations, and with improvements in performance (supercompensation) in the long term. It also reduces the risk of injury, maladaptations and decreased performance (overtraining) associated with rapid, excessive or insufficiently recovered overloads (typical of changing periods within a season).

Specificity

Neuromuscular and metabolic adaptations are specific to the stimulus applied, so training must take into account the pattern and intensity of the movements, and the energy systems and muscle groups involved. Therefore, sprint training must be fundamentally high intensity and high power, including both running and strength work of the muscle groups involved in sprinting.

Individualization
All sprint training should be programmed based on the individual characteristics of the athlete: age, anthropometry, training level, recovery capacity and strength-speed profile. In order to prevent injury and improve performance, the masters sprinter must reduce the total volume of training, increase recovery periods between sessions and microcycles, and prioritize strength work.

Periodization
Periodization is the systematic and structured planning and variation of training in order to reach one or two performance peaks, coinciding with the main competitions of the year. Periodization is divided into work cycles, which can be of three types: Macrocycles (1-2 quarters), which coincide with the indoor or outdoor track seasons; Mesocycles (1-2 months), which focus on specific objectives (capacity or power, mainly alactic and lactic) depending on the time of the season (pre-season, pre-competition or competition); Microcycles (1-4 weeks), which include weekly work sessions (running or strength), alternating loading and recovery weeks (generally in a 2:1 or 3:1 ratio). In general, there are two types of sprint periodization: Downward, in which the beginning of the macrocycle is focused on the long sprint (speed endurance) and the end on the short sprint (acceleration and power), being typical of 200-400 meters sprinters; Upward, in which the beginning of the macrocycle is focused on the short sprint and the end on the long sprint, being typical of 60-100 meters sprinters (Kasper, 2019; Haugen et al., 2019).

SPRINT TRAINING

Based on the principle of specificity there are three types of sprint training methods: Primary methods, which are specific workouts that simulate the sprint movement pattern, such as running technique drills (bounces, jumps, bounds or hurdles) and the sprints themselves (different distances, intensities and rests); Secondary methods, which are equally specific workouts that reproduce the sprint action but with resistance (sled, parachute, weighted vest or uphill) or assistance (elastic cord, motor device or downhill); Tertiary methods, which are less specific workouts that develop capacities useful in sprinting, such as strength work (free weights or weight machines), plyometrics (horizontal or vertical jumps) and stretching (static, dynamic or ballistic).

More specifically, sprint training sessions must be programmed based on the desired capacity or phase of the 100-meter sprint to be worked on: acceleration (first third), maximum speed (second third) and deceleration or speed endurance (last third) (Haugen et al., 2019).

Acceleration
The acceleration phase in the 100-meter sprint comprises the first 30-40 meters, the energy system involved is the alactic anaerobic system and the ground reaction forces (GRF) will have a predominance of horizontal forces. In the masters sprinter there is a decrease in the acceleration capacity at a rate of 1% per year as a consequence of dynapenia and a reduction in effectiveness when applying the GRF (especially the horizontal forces), which is why their work is a primary objective of the training (Pantoja et al., 2019; Haugen et al, 2019).

The recommended work are 20 to 40-meter distances on hard surface (track), 100% intensity, starting blocks or three-point start, full recovery (1 minute for every 10 meters) and a total volume of 100-300 meters. From a technical point of view, the focus should be on executing the triple extension (hip-knee-ankle) with the trunk inclined at 45º, performing very powerful anterior-posterior supports and with longer contact time with the ground (especially during the first 4 steps) (Haugen et al, 2019).

Similarly, resisted sprint work (overload) is recommended over the same distance, surface, intensity and rest as free sprinting, but with half the volume (so that a transfer to free sprints can be performed immediately afterwards). The resistance applied must not alter the movement pattern or running technique (especially stride length), so the recommended sled/vest load is 10-20% of body weight, parachute surface 1.2 x 1.2 meters and uphill incline 10-20% (Haugen et al, 2019; Alcaraz et al., 2018; Leyva et al., 2017).

Maximum speed

The maximum speed phase in the 100 meters comprises the second 40-50 meters, the predominant energy system is also the alactic anaerobic and the GRF will have a predominance of vertical forces (Pantoja et al., 2019; Haugen et al, 2019).

The recommended work are 20 to 30-meter distances with a running start (acceleration distance 10-20 meters), 100% intensity, full recovery (1 minute for every 10 meters including acceleration distance) and a total volume of 50-200 meters (without including acceleration distance). Technically, the focus should be on keeping the hips high and performing very fast up-down supports with minimal ground contact time (Haugen et al, 2019).

Likewise, assisted sprint work (superspeed) is recommended over a distance of 20 meters with a running start, 105% intensity, full recovery (1 minute for every 10 meters including the acceleration distance) and a volume of 60-100 meters. The assistance applied must optimize the movement pattern or running technique, by decreasing ground contact time and increasing stride length and stride frequency (especially the latter), with the recommended load on the elastic cord being 5-30% of body weight, 40-50 N on the motor device and the downhill incline 5-10% (Haugen et al, 2019; Leyva et al., 2017).

Speed endurance

The deceleration phase or speed endurance in the 100 meters includes the last 20-30 meters, the GRF will also have a predominance of vertical forces and the predominant energy system is also alactic anaerobic but with the participation of lactic anaerobic (Pantoja et al., 2019; Haugen et al, 2019).

In this section it is important to differentiate two concepts and their forms of training: Anaerobic power or lactate resistance, which measures the maximum peak energy that can be generated in 90 seconds (mainly between 15 and 45 seconds). It improves performance in the last third of the 100 meters and, above all, in the second half of the 200 and 400 meters. The recommended work are 80 to 300-meter distances, intensity 95-100 %, full recovery (1 minute for every second of sprinting) and a total volume of 300-1000 meters; Anaerobic capacity or lactate tolerance, which measures the total amount of energy available that can be maintained in 90 seconds (mainly between 45 and 90). This is the basis on which to develop anaerobic power and allows repeating series or sprint races at maximum intensity during work sessions or competitions, so it is essential during the preseason and early season. The recommended work are 100 to 500-meter distances, intensity 80-95%, incomplete recovery of 1-6 minutes (maximum lactate level that allows performing the next series at the same intensity), and a total volume of 600-2000 meters. From a technical standpoint, in both types of work the focus should be, in addition to the technical considerations of the maximum speed phase, on maintaining a relaxed body posture and facial expression (ideally in all phases), and a wide arm swing ("*hands to the face*") (Haugen et al, 2019).

RESISTANCE TRAINING

Most of the scientific research on aging and sport points to resistance training as the most critical or important factor in maintaining maximal capacity for both physiological aging and sport performance. Moreover, considering the importance of strength work in sprinting, it becomes a fundamental pillar of any training program for the masters sprinter and should occupy a predominant role as the aging process progresses (Fragala et al., 2019).

Resistance training must be periodized throughout the season according to the objectives of each cycle, whether they are the morphological muscle adaptations (hypertrophy) of strength work and specific to the beginning of the season, or the neuromuscular functional adaptations (coordination and recruitment) of power work and specific to the end of the season.

More specifically, training sessions must be programmed based on the type of strength to be worked: maximal strength, explosive strength, reactive strength and preventive strength. Regardless of the type of work, it seems that strength training based on speed of execution produces better adaptations with a lower total volume of work (and therefore less risk of injury) than that based on percentage of maximum repetition or 1RM (100% of maximum load that can be moved in a single repetition) (Suchomel et al., 2018; Hartmann et al., 2015; Coratella et al., 2022).

Maximal strength

Although maximal strength training does not have a specific transfer to sprinting, it is the foundation on which two other types of strength are built—explosive and reactive—which are more specific to sprinting and is critical during the preseason and early season. The goal is to move loads ≥80% of 1 RM. Maximum strength work produces improvements mainly in muscle hypertrophy (increase in the transverse diameter of muscle fibres), intramuscular coordination (recruitment of muscle fibres) and intermuscular coordination (predominant action of agonist and synergist muscles over antagonists within muscle groups), but also on neuromuscular function (recruitment of motor neurons and motor units). Likewise, maximal strength work presents greater performance on the horizontal force vector and, therefore, greater transfer to the acceleration phase of the sprint (Suchomel et al., 2018; Hartmann et al., 2015; Coratella et al., 2022; Loturco et al., 2018).

Multi-joint exercises with free weights (Olympic bar or dumbbells) are recommended, highlighting squats with all their variants (back, front, Bulgarian, pin, and overhead), deadlift and hip thrust for the lower limb; and bench press, military press, rowing-bar and pull-up for the upper limb. The recommended work are sets of 4-8 RM (80-90%), 2-3 minutes recovery and a total volume of 3-5 sets. Technically, the focus should be on keeping all joints aligned and performing a slow eccentric phase and a fast concentric phase. Deterioration of technique and moderate loss of execution speed (up to a maximum of 25%) are very useful indicators for programming recoveries and the total volume of work sessions, as well as for considering their end when they appear (Suchomel et al., 2018; Hartmann et al., 2015; Coratella et al., 2022; Loturco et al., 2018; Hickmott et al., 2021; Held et al., 2022; Dorrell et al., 2020).

Within the maximum strength work, the star exercise for sprinting is the back squat. It is especially important for the acceleration phase where the horizontal GRFs that depend on the leg extensors (gluteus maximus and quadriceps) predominate. There is a clear correlation between maximal strength (1 RM) in squat and performance improvement (3%) in 30-meter sprint. A point of controversy is the range of motion (ROM) used and the benefit it can provide: full or deep squats (120-140º) produce an overall improvement in maximal strength and greater specific activation of the gluteus maximus, but present greater technical difficulty (joint alignment and sticking point) and greater joint work (especially the knees); Partial squats—half squat (90º) and quarter squat (45º)—work a similar joint movement pattern to the sprint (especially the quarter squat), produce greater improvement in that specific ROM, allow supramaximal loads (105-110% of 1 RM of the deep squat) and present less technical difficulty and joint distress (important in the masters sprinter), but produce less gluteus maximus activation. Therefore, both types of squats should ideally be combined throughout the season, with deep squats prevailing during the preseason (working the maximal strength base at full ROM) and, subsequently, incorporating partial squats as the competitive period approaches (working maximal strength at a more specific ROM for sprinting) (Möck et al., 2021; Fossmo et al., 2022; Seitz et al., 2014; Bazyler et al., 2014; Valamatos et al. 2018).

Explosive strength

Explosive strength or power training has a great specific transfer to sprinting and is fundamental during the season, especially in the final part of the macrocycle. The goal is to move loads of 30-80% of 1 RM at maximum speed. Explosive strength exercises allow acceleration to be maintained throughout the movement unlike maximal strength exercises, where a deceleration of the load is required at the end of the movement (it can take up to 45% of ROM at loads close to 1 RM). Explosive strength work produces improvements mainly on neuromuscular function (recruitment of motor neurons and motor units), but also at the level of intramuscular and intermuscular coordination. Likewise, explosive strength work has greater performance on the vertical force vector and, therefore, greater transfer to the maximum speed phase of the sprint (Suchomel et al., 2018; Möck et al., 2021; Morris et al., 2022).

Free weight multi-joint exercises (Olympic bar) are recommended, highlighting the Olympic lifts (snatch, clean and jerk) with all its variants (power, hang and pulls) and jump squats. The recommended work are sets of 2-4 repetitions with a load of 30-80% of 1 RM (30-60% for jump squats and 60-80% for Olympic lifts), recovery of 2-3 minutes and a total volume of 2-4 sets. Technically, focus should be on performing the concentric phase at maximum speed (especially the triple hip-knee-ankle extension during the second pull phase), controlling all the sub-movements that make up the Olympic lifts (deadlift, clean/snatch pull, front/overhead squat and jerk) and cushioning the catching of the barbell (Olympic lifts) or jump landing (jump squat). Deterioration of technique and moderate loss of execution speed (up to a maximum of 25%) are very useful indicators for programming recoveries and the total volume of work sessions, as well as for considering their end when they occur (Suchomel et al., 2018; Möck et al., 2021; Morris et al., 2022).

Within the explosive strength work, there are some star exercises for sprinting: weightlifting pulling derivatives (clean/snatch pull, mid-thigh pull, hang high pull, and jump shrug). These are variants of the clean and snatch that focus on the second pull and eliminate the barbell catch (fundamental in learning the complete movement). They are especially interesting for the masters sprinter, as they specifically work the triple hip-knee-ankle extension (the determining movement in the sprint) with less technical difficulty and less joint effort. They also allow to increase the workload (80-100% of 1 RM) in earlier phases of the season (Suchomel et al., 2015; Suchomel et al., 2022).

Reactive strength

The reactive or elastic strength training par excellence is plyometrics, which consists of jumping at different intensities. It is an excellent method for transferring any type of strength work to sprinting and jumping, and for preventing injuries (it favours collagen synthesis in the connective tissue), so its training is very beneficial throughout both the season and off-season. The aim is to optimize the stretch-shortening cycle of the muscle, through an initial eccentric contraction that facilitates and enhances a more efficient subsequent concentric contraction (the transition phase between the two must be very fast so that the kinetic energy produced is not dissipated in the form of heat). Plyometric work produces an improvement in sprinting performance (up to 0.1 seconds in 50 meters) and jumping (up to 4 cm). Horizontal jumps (especially unilateral exercises) appear to provide 20-25% more peak power (especially in the ankles) and greater transfer to sprinting than vertical jumps, but they also generate greater joint stress and should therefore be limited (Suchomel et al., 2018; Morris et al., 2022; Lievens et al., 2021; Watkins et al., 2021).

Horizontal jumping exercises (bounces and bounds) and vertical jumping exercises (hurdles and box) are recommended, both low intensity (bounces and hurdles/box <30 cm) and high intensity (bounds and hurdles/box >30 cm). The recommended work are sets of 4-8 jumps, 1-2 minutes recovery and a total volume of 60-200 low intensity jumps and <60 high intensity jumps. High intensity sessions must be separated ≥1 week (Lievens et al., 2021; Watkins et al., 2021).

Preventive strength

Injuries—acute and overload—are a constant threat to the masters sprinter, due to the aging or degeneration of the musculoskeletal system and the stress to which the tissues involved in sprinting are subjected. The main risk factors for injury are previous injuries, muscle agonist/antagonist imbalance, muscle overload/fatigue, poor warm-up, and dehydration. The muscle-tendon unit contributes to 51% of a joint's flexibility and sends information to the central nervous system (via proprioceptors) about body posture, centre of gravity and joint angular velocity. Preventive strength training therefore reduces the risk of injury by up to 70% and is recommended throughout the season (perhaps more so in pre-season) and also in the off-season. The aim is to strengthen and precondition the muscles and tissues adjacent to joints and muscles, redistributing the total load. This effect is dose-dependent, so that a 10% increase in strength training volume is associated with a 13% reduction in relative risk. Preventive strength training includes eccentric work, which produces a lengthening of muscle fascicles and improves ROM comparable to ballistic stretching (although less than static stretching); and proprioceptive work, which strengthens tendons and ligaments and improves core stability, centre of gravity control, pelvic control and limb coordination (Lauersen et al., 2018).

Within the eccentric work, exercises with weight machines are recommend, preferably unilateral, highlighting the hip and knee extensions, the femoral curl, and the calf and soleus raises. The recommended work are sets of 6-8 repetitions with a load of 60-80% of 1 RM, 1-2 minutes recovery and a total volume of 3-5 sets. Technically, focus should be on controlling and lengthening the eccentric phase for ≥ 5 seconds (Suchomel et al., 2018; Vetter et al., 2022).

Within proprioceptive work, squats, lunges and planks on unstable platforms (pads, BOSU or Swiss ball) and with body weight or 10% more (vest, dumbbells or barbell) are recommended. The recommended work are 30-second sets circuits, 1-2 minutes recovery and 20- 30 minutes total volume. Technically, the focus should be on controlling body posture and motor gesture (Romero-Franco et al., 2012).

WARM UP

The main objectives of the warm-up are: to increase body temperature; to increase cardiac output and muscle blood flow; to optimize energy metabolism and oxygen consumption; to reduce joint and muscle stiffness; and to improve nerve conduction and muscle contraction. In order to achieve all of the above, the warm-up should include the following: aerobic running, stretching (mainly dynamic), specific sprinting exercises (running technique, progressives and starts) and post-activation strengthening (jumps or squats) (McGowan et al., 2015).

Aerobic running

Aerobic running (5-10 min at 65% of maximum heart rate) has as main objectives the increase of core temperature, cardiac output and oxygen consumption. Increasing core temperature by 1°C improves sprint performance by 2-5% by increasing ATP turnover and anaerobic glycolysis. Increased oxygen consumption improves overall performance by increasing motor unit recruitment, oxidative enzyme activity and anaerobic reserve (McGowan et al., 2015).

Stretching

Stretches are exercises whose main objectives are to increase joint mobility or range of motion (decrease muscle-tendon stiffness) and muscle performance (increase temperature and neuromuscular potentiation). Although they are routinely included as part of any sprint training program, there is some controversy about the actual benefit of the different types of stretching (static, dynamic and proprioceptive neuromuscular facilitation).

Static stretching prior to sprint, jump, strength and power training worsens performance (it does not increase muscle temperature or neuromuscular potentiation), except in athletes with a very low range of motion. It seems that this negative effect is counteracted if they are performed >15 minutes before training, the duration is <30 seconds per muscle, the intensity or amplitude is submaximal and, finally, they are followed by a general warm-up including dynamic stretching.

Dynamic stretching—speed and controlled amplitude—prior to sprint, jump, strength and power training improves performance, especially when performed at higher speeds (increases muscle temperature and facilitates neuromuscular recruitment). However, ballistic stretches—extreme speed and amplitude—appear to provide less of an improvement (they may stimulate muscle mechanoreceptors and inhibit presynaptic nerve stimulation and muscle contraction). It seems that the beneficial effect of dynamic stretching increases when performed while walking and when associated with certain strength work (front squats) and decreases when the duration or volume of such stretching is excessive.

Proprioceptive neuromuscular facilitation prior to sprint, jump, strength and power training appears to provide no benefit on performance (although the evidence is very limited) (Opplert & Babault, 2018; Peck et al., 2014; Behm & Chaouachi et al, 2011).

Specific exercises

Running technique work breaks down the sprint into simpler, easier to control movements, on which to achieve improvements and subsequent positive transfers to the full movement. It is carried out through walking, bouncing or jumping exercises (with or without hurdles), and should focus on very specific aspects, such as body posture, elevated hips and knees, forefoot support or ankle reactivity. This work improves proprioception and sprint performance (30 meters), with better overall results in exercises focused on stride frequency. The latter are associated with better times in the first 15 meters, while the exercises focused on stride length are associated with better times in the second 15 meters (Gil et al., 2019).

Acceleration sprints or build-ups (5 x 40 meters finished at 90-95%) produce an increase in nerve conduction of up to 12% and an improvement in sprint performance (50-60 meters) (McGowan et al., 2015; Gil et al., 2019).

Post-activation potentiation

Post-activation potentiation consists of short, explosive exercises (squats and jumps) prior to sprinting (1-10 minutes), which increase muscle strength and improve performance. They produce increased nerve conduction, increased recruitment of motor units (especially type II), increased contraction capacity (increased intramuscular calcium concentration) and better synchronization of muscle fibres (increased myosin phosphorylation). Potentiation work produces an increase in strength for a limited time, so it should be performed a few minutes before the sprint but with sufficient rest to avoid muscle fatigue.

Partial squats (quarter or half), with submaximal load (60-90%) and few repetitions (≤10) enhance muscle activation and improve up to 3% sprint performance (20-40 meters) after 5-10 minutes rest. They seem to have a greater effect on frequency than on stride length. Stronger athletes or athletes with greater experience in strength work (>3 years) benefit more from this type of exercise (by causing greater fatigue).

Plyometrics (depth jumps or jump squat) with few repetitions (≤10) seem to enhance greater activation than loaded squat (by producing greater specific recruitment of type II units and less fatigue), improving sprint performance (20-50 meters) by 5% after ≤5 minutes of rest. They appear to have a greater effect on stride length than on stride frequency. Less strong athletes or athletes with less experience in strength work (<3 years) benefit more from this type of exercise (by causing less fatigue) (Suchomel et al., 2018; Gil et al., 2019; Borba et al., 2017; Seitz et al., 2016).

RECOVERY TRAINING

Recovery run

Active recovery in sprinters is carried out in the form of tempo runs on the days following high-intensity training, providing the following benefits on the muscle: increases capillary density, oxygen supply and elimination of waste products; relaxes muscle tone; and improves aerobic capacity. This work should be performed on a soft surface (grass or turf), at short intervals (50-200 meters), low intensity (60-70%), with little rest (30 seconds to 1 minute), and a total volume with a 2:1 ratio with respect to sprint training (1000-2000 meters) (Haugen et al., 2019).

Myofascial release

Muscle fascia is a connective tissue that surrounds and connects all muscles, facilitating their mobility and elasticity. Myofascia can contract in response to stress or injury and produce tissue adhesions or scarring, which can promote the formation of sore spots. Myofascial release with roller or massage gun (for 1 minute per muscle) increases blood flow and reduces tissue adhesions and scarring, facilitating soft tissue restoration and plasticity. It appears to increase joint range of motion (up to 15%) and muscle performance (up to 7%) when combined with dynamic stretching during warm-up. It also promotes muscle recovery during cool down (Romero-Moraleda et al., 2020; Capote Lavandero et al., 2017).

Cryotherapy

Cold therapy (ice or cold water immersion) after sprinting or strength training decreases fatigue and delayed onset muscle soreness and improves recovery. Such repair is related more to the decrease in intramuscular temperature—reducing the inflammatory response and cellular metabolic activity—than to the decrease in muscle blood flow. Cryotherapy is most effective when a muscle temperature of 10-20ºC is reached for 10 to 30 minutes immediately after or within 12 hours after intense sessions or with little recovery time in between. However, its regular use should be avoided after routine sessions or with sufficient recovery time, as it can reduce the anabolic capacity of the muscle (decreasing protein synthesis and accumulation) and attenuate the mechanisms of muscle adaptation to training (Kwiecien & McHugh, 2021; Bleakley et al., 2012).

INVISIBLE TRAINING

Nutrition

Although the training of the masters sprinter includes low volumes and prolonged recovery periods, nutrition plays a fundamental role in optimizing performance and adaptations. Since one of the bases of sprinting is power, and power is proportional to the degree of muscle hypertrophy in relation to weight, nutrition must favour this muscle-to-weight ratio.

Energy requirements relative to body weight are not high, so carbohydrate intake must be moderate (3-6 g/kg/day). This intake should always be close to the daily training: prior to it in order to ensure energy and performance; and also after it in order to favour the replenishment of glycogen deposits in the muscle and recovery.

Protein requirements in sprinters and power-strength trainers are high, up to double the normal daily recommendations (2-2.5 g/kg/day). The aim is to promote muscle mass gain and counteract sarcopenia in advanced age, as well as the repair of damaged tissues. Intake should ideally be divided into meals with 0.4 g/kg of high biological value or rich in essential amino acids protein every 3-5 hours.

Water requirements in sprinters are not high, except in speed endurance sessions (higher volume). It appears that some degree of dehydration leading to a reduction of up to 2-3% of body weight can improve power-to-weight ratio and acceleration. Therefore, water intake during training should be adjusted to thirst and gastric tolerance, in order to avoid outright dehydration (especially in speed endurance sessions) but also hyperhydration (especially in acceleration and maximum speed sessions). This should always go hand in hand with adequate fluid and electrolyte replenishment in post-workout recovery.

One of the most important moments of sprint training is the post-workout recovery snack. Early (≤1 hour) and combined intake of carbohydrates (0.8 g/kg) and protein (0.4 g/kg) favours the rapid restoration of muscle glycogen stores, muscle protein metabolism and muscle damage generated during training. The addition of proteins to carbohydrates enhances the actions described above and, in particular, makes it possible to reduce by 30% the amount of carbohydrates necessary for glycogen resynthesis. It is also interesting to include phytonutrients—berries—in this snack (and, in general, in the daily diet), given their antioxidant and repairing effect on damaged muscle (Slater et al., 2019; Tipton et al., 2007).

Supplements

The use of supplements is quite common in sprint training and competition to enhance performance and recovery. Aside from the generic use of vitamins, minerals and amino acids, there are a number of supplements that are more specific to sprinting.

Creatine (2-5 g/day) induces the prephosphorylation of high-energy phosphates by increasing muscle stores and ATP availability. This favours performance and adaptations in short or alactic sprint training and in explosive strength work of up to 30 seconds duration.

Bicarbonate (0.3 g/kg pre-training) and *Beta-alanine* (3-6 g/day) counteract—at blood and muscle level respectively—the acidosis derived from the accumulation of lactate generated during anaerobic glycolysis (predominant energy system in sprinting). This favours a 1-3% increase in performance and adaptations in long or lactic sprint training, as well as in strength-endurance work of up to 1 minute duration.

Nitrates (10 mg/kg/day) enhance muscle vasodilation and oxygenation, especially in type II fibres. This improves performance and adaptations by 3-5% in different types of sprint training and strength work of up to 10 minute duration.

Caffeine (3-6 mg/kg pre-training) activates the nervous system, increasing neuromuscular transmission, catecholamine release and alertness, and reducing the sensation of fatigue. This produces >3% gains in performance and adaptations in sprint training and strength work of up to 2 minute duration.

BCAA (branched-chain amino acids)—leucine, isoleucine and valine—make up 30% of skeletal muscles and their supplementation (250 mg/kg/day) counteracts proteolysis or protein degradation generated during lactic anaerobic glycolysis. This promotes recovery after long sprint and strength-endurance training and reduces delayed onset muscle soreness (24-72 hours later).

Glutamine (non-essential amino acid) makes up 60% of skeletal muscles and is a precursor of glutathione (potent antioxidant) and transporter/remover of ammonia (potent toxin). Its supplementation (5-10 g/day) counteracts proteolysis, inflammation and acidosis generated during lactic anaerobic glycolysis. This favours recovery after long sprint and strength-endurance training, and reduces delayed onset muscle soreness (Slater et al., 2019; Tipton et al., 2007; Peeling et al., 2019; Tan et al., 2022; Weber et al., 2021; Coqueiro et al., 2019).

Sleep

The masters sprinter requires more sleep than normal as part of the recovery strategy. Sleep hygiene includes, as main objectives, a minimum number of hours of sleep at night and a supplement in the form of a postprandial nap.

Night-time sleep (7-9 hours) promotes the release of anabolic hormones—insulin, testosterone, somatotropin (GH) and somatomedin (IGF-1)—which promotes protein synthesis and tissue repair. This facilitates muscle recovery, prevents injuries and counteracts sarcopenia.

Short postprandial naps (20 minutes) have a beneficial effect on sprint performance by improving reaction time and acceleration, as well as increasing plasma antioxidant levels. Long naps (90 minutes) and/or not separated at least 30 minutes from the start of training are associated with sleep inertia (decreased cognitive capacity after awakening) and lack of arousal, decreasing performance. Likewise, naps should be taken before 4 p.m. so as not to interfere with nocturnal sleep (Vitale et al., 2019; Bird et al., 2013; Dattilo et al., 2011; Romdhani et al., 2021; Lastella et al., 2021).

SUMMARY

The final reflection of this review can be carried out through the following key ideas:

Less is more

The volume of training sessions should be determined and adapted based on the intensity and performance of the work, so that sessions should be reduced in volume or end with a drop in performance and/or deterioration of technique. On the other hand, recovery times must be strictly adhered to as they may modify the work objective of the session (especially when full recovery is sought). In view of the above and as a general rule, any masters sprinter training program should be planned with lower volume and higher recovery sessions and cycles.

Strength is a force for good

Strength training is one of the pillars of the masters sprinter's training and must be present throughout the season. Maximum strength work to counteract sarcopenia and preventive strength work to prevent injuries should prevail. Deterioration of technique and loss of execution speed are determining factors for optimal performance and must be taken into account when scheduling work sessions and ending them when they appear.

Listen to your body

The recovery strategy is another of the mainstays of the master sprinter's training, being definitive to improve performance and prevent injuries. Apart from the "*guideline*" in these strategies, you must "*listen to your body*" before starting each training session. Thus, if there is a sensation of muscle overload, the warm-up can be started and, if it persists, the sprint/strength work session should be modified (reduce volume and/or intensity) or move on to a recovery work session (tempo run, myofascial release and/or static stretching). If there is pain beyond the sensation of overload, do not train (do not even warm up) and consider a physiotherapy session.

Eat and nap to tune up

Invisible training should be a must-do for the masters sprinter, as it improves performance and, above all, recovery. Within this, two particularly interesting measures must not be missing because they are effective and easy to comply with: the post-workout snack and the postprandial nap.

AUTHOR CONTRIBUTIONS

Ramón Eizaga Rebollar carried out the literature search, drafted the initial manuscript, and reviewed and approved the final manuscript. María Victoria García Palacios supervised the data collection and the manuscript preparation, and critically reviewed and approved the final manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ACKNOWLEDGMENTS

We would like to recognize the dedication, effort and passion for sport of every single masters athlete and swimmer of my two hometown sport clubs, Club Polideportivo Olimpo Cádiz and Club Natación Cádiz.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

REVIEW ARTICLE

Exercise to reduce leptin on obesity: A review

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ABSTRACT

Obesity is a worldwide health problem associated with hypertension, diabetes, and cancer. An unhealthy and excessive diet, low physical activity, and a sedentary lifestyle are risk factors for obesity. Obesity causes adipokine dysfunction, one of which is leptin. Leptin is known to play a role in the regulation of metabolic homeostasis, especially in obesity. Hyperleptinemia in obesity is caused by leptin resistance, the result of excess energy intake and lack of physical activity or exercise, causing high levels of leptin in circulation. Regular physical exercise improves leptin signalling by regulating several proteins involved in signal transduction pathways in the hypothalamus. Physical exercise also reduces inflammation in the hypothalamus or acts as an anti-inflammatory. Stress on the endoplasmic reticulum is associated with hypothalamic inflammation and failure of insulin and leptin signalling. Improvement of leptin resistance is more effective in moderate and high-intensity aerobic exercise as well as resistance training carried out for >12 weeks with a frequency of exercise 3-4 times a week. Acute exercise and <12 weeks of exercise are not very effective in reducing leptin levels in obesity.
Keywords: Obesity; Leptin; Hypertension; Diabetes; Cancer; Diet; Physical activity; Sedentary lifestyle.

Cite this article as:
Suputra, P. A. (2023). Exercise to reduce leptin on obesity: A review. *Scientific Journal of Sport and Performance*, *2*(3), 289-299. https://doi.org/10.55860/KCHN3506

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Submitted for publication May 03, 2023.
Accepted for publication May 16, 2023.
Published June 03, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/KCHN3506

INTRODUCTION

Obesity is a worldwide health problem associated with hypertension, diabetes, and cancer. Over the last two decades the incidence of obesity has increased worldwide (Arroyo-Johnson & Mincey, 2016) According to the Endocrine Society, obesity also increases the incidence of death from cardiovascular disease, myocardial infarction, sleep apnoea, hepatobiliary disease, gout, and osteoarthritis (Cinteza & Cinteza, 2018; Jensen et al., 2014). According to the Global Burden of Disease Group, reported in 2017, states that since 1980 the prevalence of obesity has doubled in more than 70 countries and is also possible in other countries (Caballero, 2019) Every year, 2.8 million adults die due to overweight, and obesity. In 2016, 650 million adults aged over 18 years are obese. Of 13 percent of the world's adult population (11% of men and 15% of women) were obese in 2016 (WHO, 2021). According to the 2020 National Health and Nutrition National Survey (NHANES), the prevalence of obesity among American adults is 42.4% in the 2017-2018 year. At the age of 20-39, it was 40%, aged 40-59 it was 44.8%, aged more than 60 years it was 42.8% (Hales et al., 2017). According to the 2018 Riskesdas data, the prevalence of obesity in Indonesia was 21.8%, when compared to the year 2013 data the prevalence of obesity was 14.8%, while the 2007 data was 10.5% (Kemenkes RI, 2018). Unhealthy and excessive diet, low physical activity and a sedentary lifestyle are risk factors for obesity (Igel et al., 2017; Kim et al., 2019). Treatment of obesity requires multidisciplinary treatment, so dietary adjustments, exercise, and lifestyle changes are important components in the treatment of obesity (Igel et al., 2017). Moderate-intensity activity of 150 minutes per week is more beneficial in reducing abdominal obesity than 149 minutes per week or less (Kim et al., 2019).

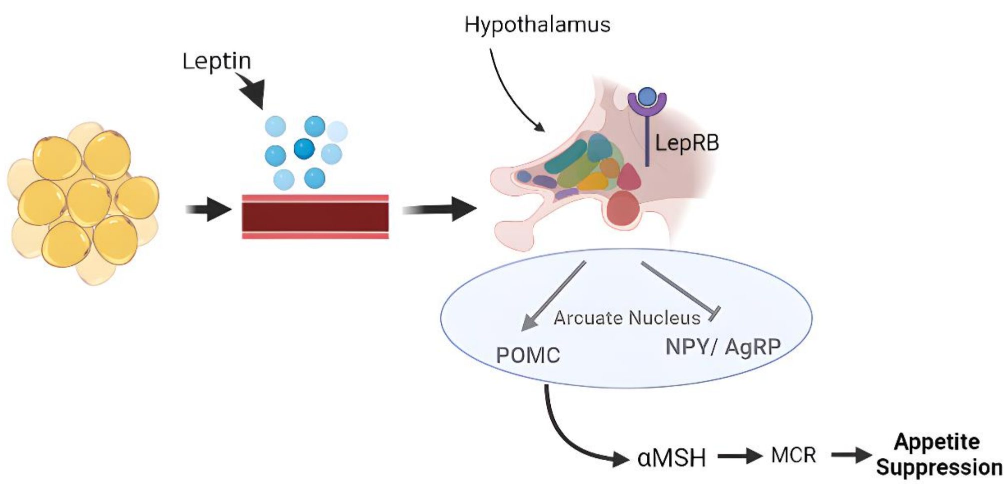
In obesity, there is an accumulation of fat mass in the body. These fats secrete adipokines which play an important role in the process of food intake, insulin action, lipids, glucose metabolism, and energy balance. Dysfunction of these adipokines will lead to obesity. Leptin and adiponectin are adipokines that are known to play a role in the regulation of metabolic homeostasis, especially in obesity (Jafari-Sfidvajani et al., 2020). Leptin, which is a product of the obesity gene, plays a role in weight control by regulating food intake and energy expenditure. Leptin acts as a hormone in energy homeostasis and also regulates neuroendocrine functions, including reproduction (Landecho et al., 2019) Increased leptin in obesity or hyperleptinemia is an etiological factor in cardiometabolic syndrome, inflammation, and malignancy. Thus obesity associated with hyperleptinemia is not only an indicator of metabolic abnormalities but plays an important role in the pathogenesis of its complications. So interventions aimed at reducing hyperleptinemia can reduce morbidity (Rostás et al., 2017).

Hyperleptinemia in obesity is caused by leptin resistance, the result of excess energy intake and lack of physical activity or exercise, causing high levels of leptin in the circulation (Fedewa et al., 2018) Increased physical activity and exercise have beneficial effects on health and are one of the therapeutics in controlling obesity, hypertension, and dyslipidaemia (Gondim et al., 2015). A meta-analysis found that resistance training can reduce hyperleptinemia without diet adjustment and significant weight loss (Rostás et al., 2017). Aerobic exercise for more than two weeks can reduce leptin, but most leptin reduction is directly proportional to weight loss (Fedewa et al., 2018) Exercise 5 weeks of high-intensity interval training (HIIT) and moderate intensity continuous training (MICT) only improves cardiorespiratory function but does not reduce leptin and body composition in obese subjects (Kong et al., 2016) Combination of aerobic exercise and resistance training for 12 weeks as a therapeutic method to improve metabolic risk by reducing leptin in obesity (Bharath et al., 2018) However, the combination of aerobic exercise and resistance training for 10 weeks with a duration of 150 minutes per week and 270 minutes per week did not significantly reduce leptin, only 450 minutes per week of exercise significantly reduced leptin in obesity (S. Li et al., 2020).

From the above background, the authors want to compile this paper to provide an overview and explain the effect of physical exercise on reducing leptin in obesity. In this paper, the authors also want to explain the intensity and frequency of exercise that can reduce leptin in obesity. The search method in this mini-review was carried out on PubMed, Science Direct, and Google Scholar search engines with the keywords "Obesity" OR "*Obese*", "*Obese*" OR "*Obesity*" AND "*Exercise*" OR "*Aerobic*", "*Aerobic*" OR "*Exercise*" AND "*Leptin*", "*Aerobic*" OR "*Exercise*" AND "*Leptin*" AND "*Obesity*" OR "*Obesity*". Obesity prevalence data was taken from the WHO website and the Indonesian Ministry of Health.

WHAT IS LEPTIN

Adipocytes are the main source of circulating leptin. The level of leptin concentration is closely related to fat cells in both humans and mice (Zhang & Chua, 2018). Leptin is a peptide hormone that plays a role in food intake, body mass, reproductive function, pro-inflammatory response in the immune system, angiogenesis, and lipolysis. Leptin is produced in white adipose tissue (WAT), and only small amounts are found in brown adipose tissue (BAT), foetal tissue, placenta, stomach, bone marrow, teeth, and brain (Obradovic et al., 2021). Apart from being a hormone, leptin also acts as a cytokine. As a hormone, leptin affects endocrine functions for energy homeostasis, while as a cytokine leptin enhances the inflammatory response. So that the increase in leptin levels in obesity contributes to the occurrence of low-grade inflammation which is a risk factor for cardiovascular disease, type 2 diabetes, and degenerative diseases (La Cava, 2017).



Note. LepRB: Leptin receptors binding; POMC: Pro-opiomelanocortin; NPY: Neuropeptide Y; AgRP: Agouti-related peptide; aMSH: alpha melanocyte stimulating hormone; MCR: Melanocortin receptors. Created in https://www.biorender.com/

Figure 1. Leptin Regulation: Adipocyte release leptin to circulation and bind leptin receptors in the hypothalamus. After binding with leptin receptors. Leptin act in arcuate nucleus to activate POMC neuropeptides (anorexigenic) and deactivate NPY/AgRP neuropeptides (orexigenic). Stimulate the release of aMSH molecules to synapse and binding with MCR to suppress appetite.

Adipocytes release leptin into circulation, then bind to leptin receptors in the hypothalamus and provide information on the amount of energy stored in the body. After binding to the leptin receptor (LepR) it regulates the activity of hypothalamic neurons also orexigenic and anorexigenic neuropeptides (Ghadge & Khaire, 2019). In preclinical trials, leptin acts in the arcuate nucleus of the hypothalamus to activate pro-opiomelanocortin (POMC) which produces anorexigenic molecules such as αMSH (a-melanocyte stimulating hormone) and deactivates orexigenic neuropeptide Y (NPY) and agouti-related peptide (AgRP) (Perakakis et al., 2021). αMSH is released into the synapse to activate neurons through binding to the melanocortin receptor (MCR) and causes appetite suppression (Obradovic et al., 2021).

Leptin binding to its receptors activates the Janus Kinase 2 (JAK2)/Signal Transducer And Activator Of Transcription 3 (STAT3), Insulin Receptor Substrate (IRS-1), Phosphoinositide 3-kinases (PI3K), mitogen-activated protein kinase (MAPK) signalling pathway. Activation of JAK2/STAT3 signalling is involved in the modulatory effect of leptin on changes in gene expression. The PI3K pathway provides more rapid signalling via the phosphorylation of a cytoplasmic protein that plays an important role in regulating food intake and arterial hypertension. However, all of these pathways play an important role in the regulation of energy homeostasis (Babaei & Hoseini, 2022; Igel et al., 2017).

Leptin binds to the Leptin receptor B (LepRb) and then activates Janus Kinase 2 (JAK2). JAK2 will undergo autophosphorylation and tyrosine phosphorylation of Tyr985, Tyr1077, and Tyr1138 in the receptor. Phosphorylation of JAK2 and Tyr985 causes phosphorylation of SH2-containing protein tyrosine phosphatase 2 (SHP2) thereby activating the MAPK/ERK pathway and causing energy homeostasis. Phosphorylation of the Signal transducer and activator of transcription 5 (STAT5) is caused by phosphorylation of JAK2 and Tyr 1077 which play a role in the reproducing effect of leptin. Phosphorylation of JAK2 and Tyr1138 activates STAT3. Tyr 1138 and STAT3 signalling binding then enter the cell nucleus, undergoing transcription of target genes, including genes from the suppressors of the cytokine signalling (SOCS3) family which are inhibitors of leptin signalling. The SOCS3 protein binds to Tyr985 at the leptin receptor and causes negative feedback on the leptin signal transduction system. SHP-2 overexpression will reduce the work of SOCS3 in inhibiting the leptin pathway through a competitive mechanism to bind to Tyr985 (Peng et al., 2021).

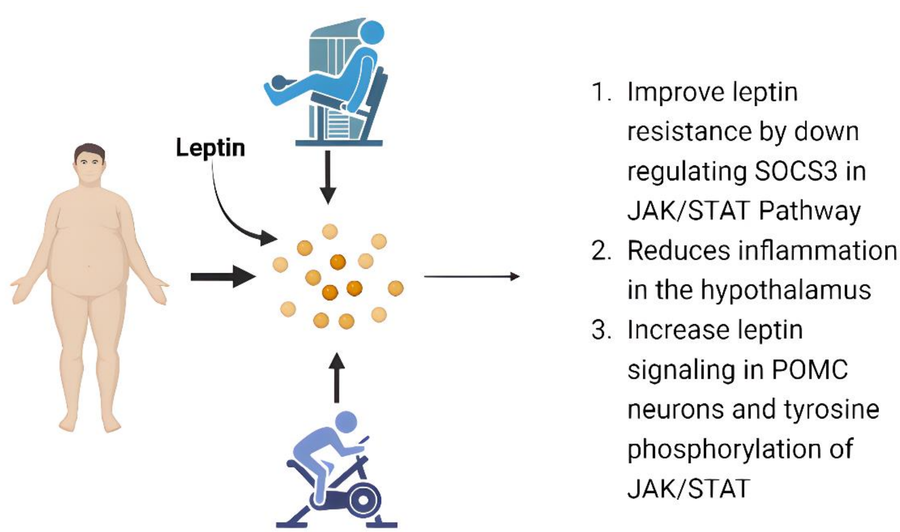
LEPTIN IN OBESITY

Increased levels of leptin are associated with obesity. In human subjects, obesity is associated with hyperleptinemia and leptin resistance (Ghadge & Khaire, 2019) Under normal physiological conditions, circulating leptin levels are proportional to adipose tissue mass. Elevated leptin levels or hyperleptinemia in obesity are associated with several metabolic disorders such as insulin resistance, and renal and cardiovascular disease (Zhao et al., 2020) In a state of endogenous hyperleptinemia, leptin dysfunction occurs which causes increased food intake, impaired nutrient absorption, and inhibition of lipid and glucose metabolism. This situation causes leptin resistance, the mechanism of which is divided into three, namely gene mutations, blood-brain barrier permeability, and disruption of leptin receptor signalling (Hwang et al., 2021). Leptin resistance occurs due to mutations in the OB and DBU genes which cause an increase in appetite, which is called hyperphagia, which is very rare. The occurrence of gene mutations causes impaired secretion of the hormone thyrotropin and growth hormones. This indicates that gene mutations are not the only cause of leptin resistance (Gruzdeva et al., 2019). In obesity, pathological changes occur in the cellular resistance of the blood-brain barrier resulting in disruption of leptin transport from the circulation to the brain. Decreased permeability of the blood-brain barrier causes an increase in circulating leptin, resulting in leptin resistance (Gruzdeva et al., 2019; Izquierdo et al., 2019). Furthermore, disruption of leptin receptor signalling can lead to leptin resistance. Impaired leptin signalling caused by hypothalamic inflammation and stress on the endoplasmic reticulum causes leptin resistance (Hwang et al., 2021).

Increased leptin levels are associated with increased body mass index (BMI) in obese subjects. BMI > 25 kg/m^2 – 30 kg/m^2 have lower leptin levels than obese subjects with BMI > 30 kg/m^2 (Sinorita et al., 2009) Obese people have higher leptin levels compared to normal weight. This is due to an increase in free fatty acids and excessive food intake causing lipotoxicity, stress on the endoplasmic reticulum, and inflammation which causes an increase in leptin levels (Bouillon-Minois et al., 2021) The increase in leptin levels was found to be higher in obese and pre-obese subjects compared to normal weight. In terms of gender, higher leptin levels were found in women than men in obese and pre-obese in Nigeria. Previous in vitro and in vivo studies concluded that there was an increase in inflammatory mediators such as tumour necrosis factor-alpha (TNF-α), c-reactive protein (CRP), interleukin-6 (IL-6), and leptin. Increased TNF-α increases circulating leptin in obesity (Sáinz et al., 2015). Increased leptin levels are in line with increases in body mass index, waist circumference, total cholesterol, triglycerides, and low-density lipoprotein (LDL) cholesterol in obese female subjects in Saudi Arabia (Al-Amodi et al., 2018). There is a relationship between leptin and insulin resistance in obese class III female subjects, but leptin is not a predictor of insulin resistance (Osegbe et al., 2016).

EFFECT OF EXERCISE ON LEPTIN IN OBESITY

Leptin is the main adipokine in obesity which indicates that there is a lot of fat accumulation that is at risk for cardiometabolic disorders (Rostás et al., 2017). Consumption of a lot of fat and a sedentary lifestyle are risk factors for obesity (Kang et al., 2013). Studies in rats and humans show the effect of exercise or exercise on reducing leptin and improving insulin resistance (Peng et al., 2021). Aerobic exercise can improve leptin resistance and reduce serum leptin levels in rats obese by downregulating suppressors of cytokine signalling 3 (SOCS3) in the JAK/STAT pathway(Babaei & Hoseini, 2022). Studies in rats that were given a high-fat diet, then given aerobic exercise for 12 weeks, significantly reduced serum leptin (Gopalan et al., 2021). Regular physical exercise improves leptin signalling by regulating several proteins involved in signal transduction pathways in the hypothalamus. Physical exercise also reduces inflammation in the hypothalamus or acts as an anti-inflammatory. Stress on the endoplasmic reticulum is associated with hypothalamic inflammation and failure of insulin and leptin signalling. Physical exercise increases leptin signalling in POMC neurons, increases tyrosine phosphorylation of JAK2 and STAT3, then migrates to the nucleus and transcribes anorexigenic neuropeptides (Rodrigues et al., 2018).



Note. SOCS3: Suppressors of cytokine signalling 3; JAK/STAT: Janus kinase/signal transducer and activator of transcription; POMC: Pro-opiomelanocortin. Created in https://www.biorender.com/

Figure 2. Effect of Exercise on leptin: exercise improve leptin resistance by down regulating SOCS3 in JAK/STAT pathway, reduce inflammation in the hypothalamus, increase leptin signalling in POMC neurons and tyrosine phosphorylation of JAK/STAT to suppress appetite.

A meta-analysis study found that resistance training was more effective in reducing leptin levels in obese elderly subjects than aerobic exercise (Rostás et al., 2017). However, according to other studies, it was concluded that moderate-intensity training reduced leptin and IL-6 in adolescent obese subjects (Many et al., 2013). Systematic review and meta-analysis concluded that aerobic exercise significantly reduced serum leptin compared to resistance training and combination exercise (Yu et al., 2017). A 12-week aerobic exercise program with a frequency of 5 times a week in obese subjects significantly reduced serum leptin (Martins et al., 2013). Moderate-intensity exercise reduced IL-6 and leptin in obese and overweight subjects who carried out an exercise program for 12 months (Gondim et al., 2015). Both aerobic and resistance exercise for 12 weeks reduced TNF-α and leptin in diabetic and non-diabetic rats (Dinari Ghozhdi et al., 2021). A systematic review and meta-analysis in obese subjects concluded that exercise for more than 2 weeks reduced serum leptin along with a decrease in body fat (Fedewa et al., 2018).

INTENSITY AND FREQUENCY OF EXERCISE ON LEPTIN IN OBESITY

Leptin is an adipokine that plays a role in the regulation of food intake and body weight. The level of circulating leptin levels is proportional to body fat mass so that obese individuals have more leptin levels than individuals with normal weight. Obese subjects experience resistance to inhibitory activity to control food and energy intake (Iikuni et al., 2008) Increased physical activity is used for the management of obesity, because of its effect on increasing energy expenditure. High-intensity exercise results in more energy expenditure compared to low- and moderate-intensity exercise (Tremblay et al., 2011) Resistance training for 12 weeks can significantly reduce leptin in obesity, but the decrease occurs most in interval resistance training compared to traditional resistance training and circular resistance training. Interval resistance training is done with 2 sets of 14 repetitions of 50% 1RM (Alizadeh et al., 2021) Interval resistance training and circular resistance training for 12 weeks, with a frequency of 3 times a week and 50 minutes each exercise is significant in reducing leptin (Ataeinosrat et al., 2022). Combination of aerobic exercise and resistance training for 12 weeks with a frequency of 5 times a week as a therapeutic method to improve metabolic risk by reducing leptin in obesity (Bharath et al., 2018) The effect of acute exercise with high-intensity interval training and moderate-intensity continuous training significantly reduced leptin both immediately after exercise and 1 hour after exercise, but both exercises increased interleukin-6 immediately after exercise (de Souza et al., 2018).

In obese rat subjects with diabetes given aerobic training and resistance training for 12 weeks, it can help significantly reduce fasting blood sugar triglycerides, LDL, TNF-α, and leptin, but after detraining for 4 weeks, there is another increase in body weight, triglycerides, TNF-α, and leptin (Dinari Ghozhdi et al., 2021). Exercise 5 weeks, with a frequency of 4 times a week with high-intensity interval training (HIIT) and moderate-intensity continuous training (MICT) only improves cardiorespiratory function but does not decrease leptin and body composition in obese subjects (Kong et al., 2016) However, a study that compared HIIT and MICT performed 3 times a week for 12 weeks concluded that both exercises were effective in reducing leptin, but there was a greater decrease in leptin in HIIT (-0.35pg/ml) than in MICT (-0.16 pg/mL) (Hooshmand Moghadam et al., 2021). The combination of aerobic exercise and resistance training for 10 weeks with a duration of 150 minutes per week and 270 minutes per week did not significantly reduce leptin, only 450 minutes per week of exercise significantly reduced leptin in obesity (S. Li et al., 2020) Aerobic exercises such as badminton, cycling, jogging, sports games for 16 weeks with a duration of 240 minutes per week in obese female subjects aged 7-22 years, can significantly reduce leptin levels. The decrease in leptin is probably caused by a decrease in fat mass, intensity, and time of exercise (C. Li et al., 2022) Exercise for 8 weeks, 2 times a week, both aerobic exercise and resistance training, combined with a low-calorie diet, cannot reduce leptin levels (Muhammad et al., 2021) The combination of Aerobic exercise and resistance training compared to HIIT for 12 weeks with a frequency of 3 times a week are equally effective in reducing leptin levels in postmenopausal obese subjects, but HIIT is more effective in terms of exercise time (Nunes et al., 2019) HIIT in obese women with a frequency of 2 times a week for 3 weeks, not effective in reducing leptin levels. This conclusion can be seen from the results of the reduction with acute HIIT exercise on day 1 after exercise not much different from day 19 after exercise (Vardar et al., 2018). Exercise <12 weeks did not produce a significant effect on reducing leptin in obesity, compared to exercise >12 weeks both on aerobic exercise as well as resistance training (Yu et al., 2017) The combination of a low-carbohydrate diet and a low-fat diet with HIIT is more effective at reducing leptin than the HIIT intervention alone in obese type 2 diabetes subjects (Asle Mohammadi Zadeh et al., 2018).

CONCLUSION

Obesity is a worldwide health problem associated with hypertension, diabetes, and cancer. Over the last two decades, the incidence of obesity has increased worldwide. In obesity, there is an accumulation of fat mass in the body. These fats secrete adipokines which play an important role in the process of food intake, insulin action, lipids, glucose metabolism, and energy balance. Dysfunction of these adipokines will lead to obesity. Leptin and adiponectin are adipokines that are known to play a role in the regulation of metabolic homeostasis, especially in obesity. Increased leptin in obesity or hyperleptinemia is an etiological factor for the cardiometabolic syndrome, inflammation, and malignancy. Hyperleptinemia in obesity is caused by leptin resistance, the result of excess energy intake and lack of physical activity or exercise, causing high levels of leptin in circulation. Increased physical activity and exercise have beneficial effects on health, and become one of the therapeutics in controlling obesity, hypertension, and dyslipidaemia. Regular physical exercise improves leptin signalling by regulating several proteins involved in signal transduction pathways in the hypothalamus. Physical exercise also reduces inflammation in the hypothalamus or acts as an anti-inflammatory. Stress on the endoplasmic reticulum is associated with hypothalamic inflammation and failure of insulin and leptin signalling. Improvement of leptin resistance is more effective in moderate and high-intensity aerobic exercise as well as resistance training carried out for >12 weeks with a frequency of exercise 3-4 times a week. Acute exercise and <12 weeks of exercise are not very effective in reducing leptin levels in obesity.

SUPPORTING AGENCIES

No funding agencies were reported by the author.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

ACKNOWLEDGEMENT

The author would like to thank you Prof. Dr. I Made Jawi, M. Kes, Dr. I Made Muliarta, M. Kes, and Dr. Susy Purnawati, MKK for the support and guidance.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

An exploratory investigation of traditional scoring in diving and relationships to the development of Artificial Intelligence opportunities

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ABSTRACT

This study investigated the conceptions of perfection that figure in the minds of divers, coaches, and judges. Additionally, consideration was given to their views of whether an Artificial Intelligence (AI) based scoring system could be relied upon to yield authentic results, allied with the desirability of its use. Six participants (2 each of diver, coach, judge) were interviewed. Following verbatim transcriptions, thematic analyses were conducted to identify commonly occurring themes relevant to diving and its scoring system. The results of this preliminary study have shown a leaning towards clarification of the rules on point deductions by FINA (Fédération Internationale De Natation/ International Swimming Federation). Furthermore, the concept of perfection in diving changes from country to country and culture to culture, providing further difficulties in the objectivity of judging and there was a call for openness and clarity. With the human element of judging carrying weakness and allowing for errors, subsequently, it was felt by the respondents that some parts of a dive should be measured with technology where feasible. There was a consensus that judges could not be fully replaced without substantive changes to the sport of diving, in effect losing the artistic element that is subjectively assessed.
Keywords: Performance analysis of sport, Perfection, Technology, Judging, FINA, World Aquatics, AI.

Cite this article as:
Jakab, S., Davis, P., & Whyte, I. (2023). An exploratory investigation of traditional scoring in diving and relationships to the development of Artificial Intelligence opportunities. *Scientific Journal of Sport and Performance*, 2(3), 300-313. https://doi.org/10.55860/QELM3130

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Submitted for publication May 08, 2023.
Accepted for publication May 16, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/QELM3130

INTRODUCTION

High level sport and the demand for excellence can be considered bedfellows, albeit what constitutes excellence continues to be debated (see Devine, 2022). Not in doubt is that excellence, as posited by Devine, is conducive to winning (within the permitted means) and is multi-dimensional, constituted by physical, intellectual, and volitional capacities (p.197). Yet, the literature has outdistanced excellence in the concept of perfectionism, with Hill, Jowett and Mallinson-Howard (2017) asserting that perfect performance and the perfect body are not only desirable, but are perhaps revered in sport, dance, and exercise. They recognise the healthy and defining character of perfectionism for elite performers as well as its more negative ramifications for athletes (e.g., Flett and Hewitt, 2014, 2016; Hall,2016). Working definitions of perfection include "*striving for flawlessness*" (Stoeber and Childs, 2011, p. 2) and "*demanding of oneself or others a higher quality of performance than is required by the situation*" (Hollender, 1978, p. 384). Thus, judging standards in artistic sports such as skating, diving, gymnastics, and winter and summer aerial sports (e.g., skateboarding and snowboarding) are set against the standards of hypothetical "*ideal (perfect) models*" of technical and artistic performance.

Perfection is a much-debated construct in philosophical literature (e.g., Breivik, 2010). However, this study was not intended to theorise perfectionism as a specific topic, but to draw on the sports literature for a working definition that is applied when judging sports by awarding points against defined and undefined values. Perfection in sports settings is context-dependent, therefore domain-specificity must be explored prior to the examination of perfection (Anshel and Eom, 2003; Dunn *et al*., 2005; McArdle, 2010). According to Dunn *et al*. (2005), the move towards domain-specificity is key when defining or assessing perfection. Perfection in football and diving, for instance, are modular and not comparable. One reason may be found in Best's (1978, pp. 101-103) distinction between what he calls aesthetic and purposive sports, the difference inhering in the respective relationships between means and ends. For example, in football (a purposive sport), the aim is to score goals, and as long as they are within the rules, the manner of their scoring does not matter. They all count equally. In aesthetic sports (such as diving, gymnastics, and skating) by contrast, the ends are inseparable from the means of their production. Skill is essential.

Moreover, perfection goes beyond being victorious in a contest or competition. Aesthetic sports performance is judged against a measure of suggested perfection, with maximal scores of 10 the "*gold standard*" of perfection in many of them. The most memorable example is Nadia Comăneci, the first gymnast to receive the "*perfect 10*" from judges (Comăneci, 2009; Stirling *et al*., 2020). Gymnastics no longer uses that scoring system, instead opting for an unlimited score, with difficulty marks providing infinite possibilities to raise score levels.

In the sport of artistic diving, judges are physically separated on the poolside, resulting in different perspectives while observing a dive. The exact physical differences depend on competition level, the number of judges, the layout of the pool, and other factors such as COVID-19 social distancing measures. This presence of such a variable contributes confounding factors to competition organisation and outcomes, bringing with it domain-specific judging. Such a phenomenon has never been investigated in artistic diving but given its presence and its potential impact on judging, there is a need for study, incorporating the views of competitors, coaches, and officials.

Presence of technology in sport

In attempts to minimise human error and provide greater transparency, some sports have already introduced video technology. Video Assistant Referee (VAR) was adopted by the International Football Association

Board (IFAB) and is now used extensively via a variety of technological systems (IFAB, 2018), while tennis has the "*Hawk-eye*" line examination system (Hawk-Eye Innovations Ltd., Sony Business Europe, Basingstoke, England) to enhance and sometimes replace the line judges who use the naked eye (Spitz *et al*., 2021; Yan and Xin, 2021). In some cases, the main aim of introducing AI was not to limit human error, but to assist with score prediction in sports or injury risk assessment/prevention (Li and Xu, 2021; Claudino, *et al*., 2019).

Artistic sports (Best's "*aesthetic*" sports), in which competition is not decided by distance or time measurement, have not yet used technology as a tool to assist judges. However, the revolutionary work of Fujiwara and Ito (2018) could create an outline for judging artistic competitions in the future. With the aim of improving fairness by removing human error and bias, therefore increasing the objectivity of a subjective system, a 3D laser technology has been created. The International Gymnastics Federation (FIG) tested the system in 2019 at the World Artistic Gymnastic Championship, and the final tests took place in Liverpool in late 2022 (Takaomi, 2021). The system is based on Artificial Intelligence. A scanning unit uses lasers to analyse motion, while joint position recognition software assesses angles of body segments such as arms, legs, and ankles. Finally, performance data is compared to database models, to create numerical data on similarities and differences of the angles of segments and deduct points accordingly. Critical review of the system was conducted, including interviews with judges, coaches, and gymnasts. The study identified possible benefits for gymnastics, as well as potentially negative impacts. Possible benefits included demystification of the sport, making it easier for the public to understand what is judged and why, and improvement of the validity and reliability of judging through the reduction of subjectivity. Possible drawbacks attached to the complexity of judging artistic components, with the majority of respondents believing that the AI system could not judge the artistic elements of gymnastics (Allen, *et al*., 2021). There were also concerns that the role of judges could be devalued, with consequences for recruitment and retention. Additionally, concerns were noted around potential impacts to some of the sport's traditions (Allen, *et al*., 2021).

Other concerns surface when the current scoring rules are considered with rules and point deductions being based on pictorial illustrations and vague descriptions (Fujiwara and Ito, 2018). However, descriptions include point deductions for "*slight bend*" or "*strong bend*", which are not yet possible to identify with present technology.

Judging in the sport of diving

In diving, similar issues are present and similar clarifications are necessary before consideration of technology as an addition to or a replacement for judges. For example, the Diving Officials Manual (2017-2021) of the Federation Internationale de Natation (FINA, 2020) describes a dangerous dive as a dive in which the diver's head is "*unsafely close*" to the platform or diving board. This is a subjective measure and marks will be deducted according to a judge's perception of what is "*unsafely close*". Likewise, deductions (Table 1) for faults such as "*insufficient height*" or "*off to the side*" without hitting the platform or springboard' are "*according to own opinion*".

Since competitive diving is a sport in which the notion of perfection is salient (judges can award a "*perfect 10*"), and a sport with demands for greater transparency and accuracy in judging, this study was designed to investigate the concept of perfection in diving. With the advancement of technology in sport, there is a growing need to consider conceptions of the potential role(s) of Artificial Intelligence (AI) in offering greater transparency and fairness in diving competitions. This study had three research questions (RQ):

RQ (1) What are the conceptions of perfection that figure in the minds of divers, coaches, and judges?

RQ (2) According to divers, coaches, and judges, would an AI-based scoring system be able to capture perfection in a dive and therefore be relied upon to yield authentic results?
RQ (3) According to divers, coaches, and judges, what is the final desirability of an AI-based scoring system?

Table 1. Judges guide for points deductions during the flight of a dive (from FINA, 2020).

Fault	Range of deduction
Insufficient height	½ to 2 points
Dive is too close to the board (but does not hit the springboard or platform)	According to own opinion
Dive is too close to the board with the head (but does not hit the springboard or platform)	2 maximum awards
Diver hits the springboard or platform with feet or hands (does not affect the dive)	According to own opinion
Diver hits springboard or platform with the head	2 maximum awards
Dives off to the side (would have hit springboard or platform with the head and would have affected the dive)	2 maximum awards
Dives off to the side but would not have hit springboard or platform	According to own opinion

METHODS

Participants
Following ethical approval from the University of Sunderland Research Ethics Group (number 011065), purposive sampling (Bernard, 2002) was employed to identify and recruit participants. Participants were sent an outline of the study, including its aims and the means by which anonymity would be ensured. If comfortable with the details, participants were asked to sign and return an Informed Consent form.

In accordance with Mears (2009, cited in Allen *et al*., 2021), six participants (3 male, 3 female) were recruited for interviews. They had to meet criteria. First, participants were needed from the categories of judge, coach, and diver (albeit these distinctions can be fragile in practice, given the common plural occupation of roles across careers in diving). Second, participants had to cover as wide a base of competition level, location, and culture as possible. This, again, is because conception of ideal technique and understanding of the scoring system differs depending on competition level, culture, and location. (Divers, coaches and judges from Russia, China, Australia, and the UK, for instance, will all have different respective conceptions of the perfect dive.) Therefore, the participants came from a range of countries, including the UK, New Zealand, Australia, Hungary, and the Netherlands. Two participants worked for local diving clubs, representing grassroots diving. However, as the possible presence of perfectionism is more common in elite sports, the remaining four participants had Olympic experience, with a total of 11 appearances (diver or judge) between the 1980 and 2020 Olympic Games. The participants, moreover, included an Olympic gold medallist, a FINA judge, a FINA educator, a technical diving committee member, a European Championships competition director, and a Judge Evaluator (see Table 2). (Researchers were aware of the nationality of each competitor but have excluded that from the table to safeguard anonymity).

Data collection
A qualitative design was employed to collect, compare, and analyse descriptive data, gathered from semi-structured interviews. The advantages of using semi-structured interviews have been outlined by Wilson (2014) cited by Allen *et al*. (2021) as the method offers a form of structure while allowing flexibility for new insights from interviewees. The interviews were conducted online (Zoom Video Communications, Inc., San

Jose, California) due to geographical limitations and the need for social distancing due to COVID-19. An *aide-memoire* / topic guide (Irvine, Drew and Sainsbury (2013) was employed to steer the interviews, which were audio recorded to ensure accuracy for subsequent *verbatim* transcription.

Table 2. Participants' personal details.

Participants	Sex	Age	Current Role	Highest personal competition level
P1	F	59	Judge	Olympic Games
P2	F	49	Coach	National
P3	F	32	Diver	Olympic Games
P4	M	40	Judge	Olympic Games
P5	M	53	Coach	International
P6	M	34	Diver	Olympic Games

Data analysis

Following the six steps set out by Braun and Clarke (2006), inductive thematic analysis of the interview transcripts was conducted by the first and third author, to identify commonly occurring patterns and themes (Joffe, 2012; Braun and Clarke, 2014; Maguire and Delahunt, 2017). We first familiarised ourselves with the data by reading and re-reading the responses. Codes were next identified independently by both authors, and subsequently themes were created. In the fourth step the themes were reviewed, and in the fifth step they were named. Subsequently, meetings were held between all three authors, where the themes were reviewed and discussed until a consensus was reached. Finally, the themes were written up by the first author, checked by the third author, then reviewed by the third author. Although coding is subjective and interpretative, and coding by multiple individuals is not necessary to enhance rigour (Braun and Clarke 2019), we felt it important that at least two researchers be involved in the analysis. The study was reported according to the Standards for Reporting Qualitative Research (SRQR) (O'Brien *et al.*, 2014).

RESULTS

Following *verbatim* transcription of the interview recordings, a total of 16, 435 words were presented for analysis using a hybrid approach of inductive and deductive methods, as outlined by Fereday and Muir-Cochrane (2006).

The study was designed to consider the *Concept of Perfectionism* [in diving], based on the participants' backgrounds and experiences, as well as to consider their views of *Acceptance of Technology* [AI]. Those two constructs became General Dimensions, under which all themes and categories would be allocated. One hundred and thirty-nine meaning units were identified. These were distilled to 19 themes, which were reduced to 8 categories.

Under the General Dimension of *Concept of Perfectionism* four categories were identified: y "*Attainability?*" "*Influencing Factors*", "*Terminology*", and "*Appropriateness*". Similarly, *Acceptance of Technology* elicited four categories: "*Positive Aspects*", "*Negative Aspects*", "*Logistics*", and "*Regulatory Issues*". Each of the eight categories held between one and five themes (see Figure 1 for fuller descriptions and Figure 2 for exemplar statements of each theme).

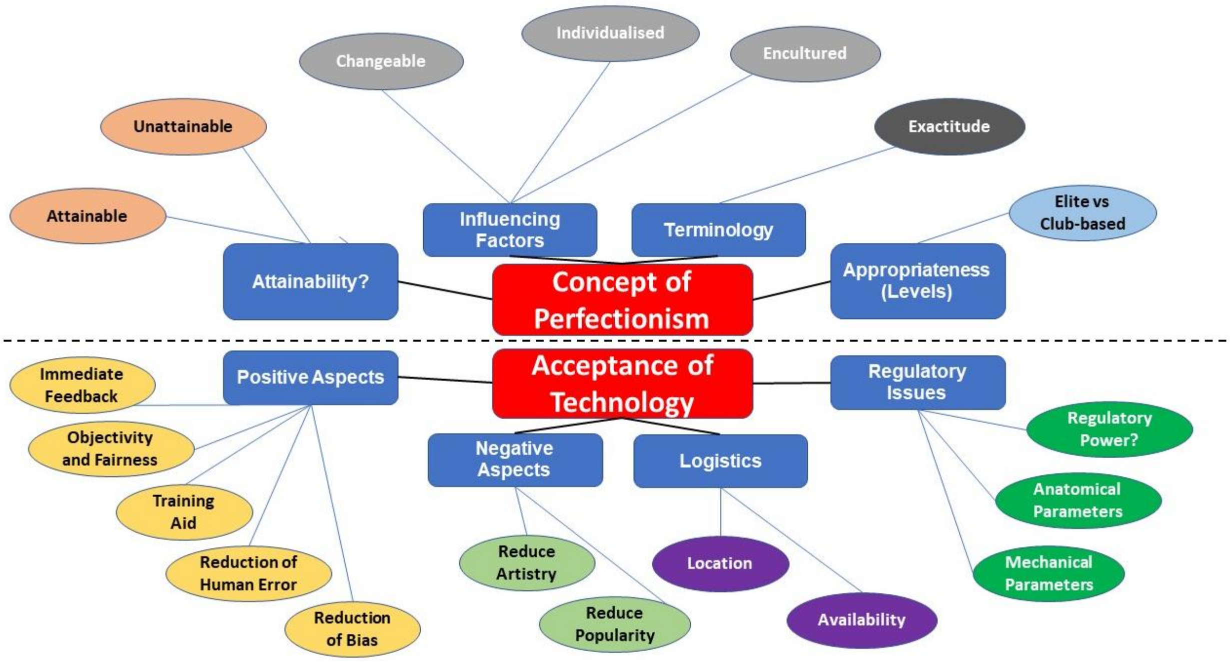

Figure 1. Diagrammatic representation of the findings following analysis of semi-structured interviews with divers, coaches, and judges showing General Dimensions of Concept of Perfectionism and Acceptance of Technology each with four associated categories and their relevant themes.

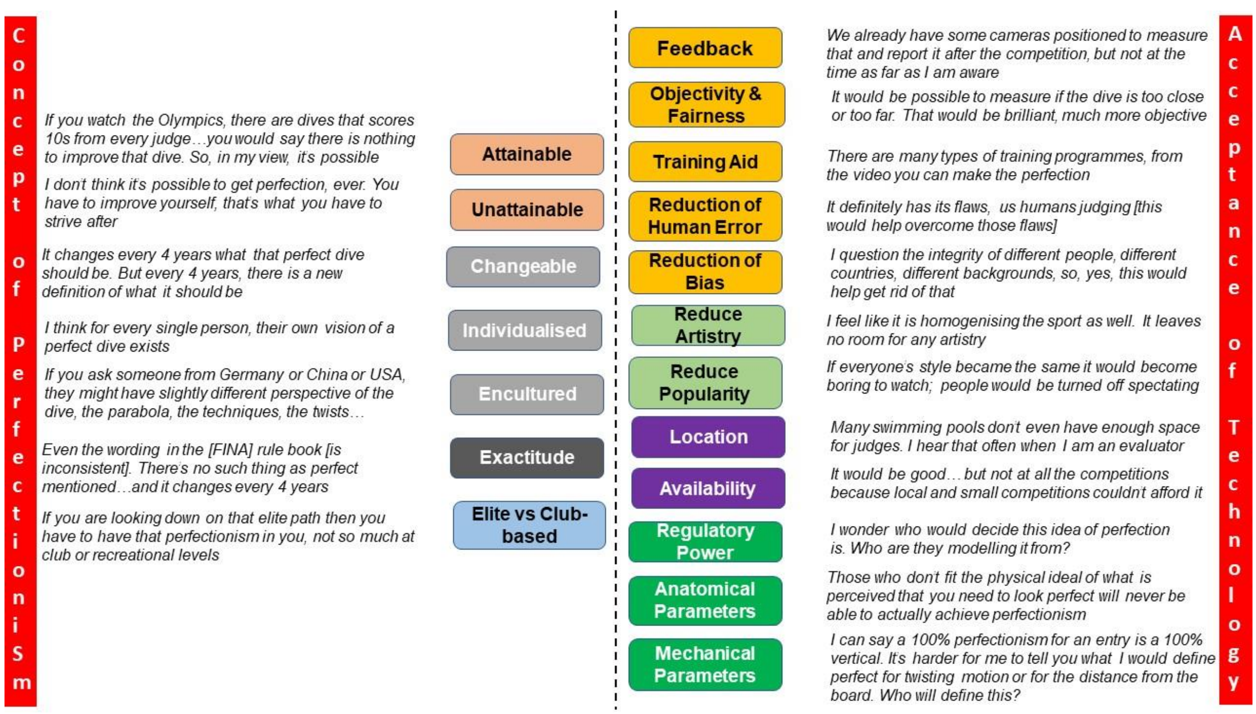

Figure 2. Diagrammatic representation of the findings following analysis of semi-structured interviews with divers, coaches, and judges showing General Dimensions of C*oncept of Perfectionism* and *Acceptance of Technology and* associated themes with exemplar statements. To provide a logical presentation of the data, results are organised to reflect the research questions intimated at the outset.

RQ (1) What are the conceptions of perfection that figure in the minds of divers, coaches, and judges?
The key research findings indicated that the majority of participants do not believe that the perfect dive exists. On the side of the non-believers, Participant 3 stated candidly: "*I think there is no perfection… there is always something you can improve on.*" Participant 2 also responded negatively: "*No, you can always dive a little bit higher, there is always something that can be improved. Even if it appears to be a perfect dive*." However, the same participant then backtracked:

> *Would you say that the perfect dive is watching a computer simulation of it? And if so, I think there have been dives that have kind of followed that exact form and pattern. So, yeah, I think there probably is [such a thing as a perfect dive].* (Participant 2).

Participant 6 was less confused:

> *Technically, I think I could describe to you what a perfect dive should look like, and I could probably see [in my mind's eye] or recognise one if it was performed, but I have never seen one and I am not sure that it can be performed.*

An Olympic gold medallist diver proposed it is an "*empty pursuit*", suggesting that athletes should aim, not for perfection, but for excellence.

RQ (2) According to divers, coaches, and judges, would an AI-based scoring system be able to capture perfection in a dive and therefore be relied upon to yield authentic results?
Participants did not see a way for a computer to judge the artistry of the sport, potentially reducing the role of AI in judging.

To a direct question about whether AI should be used as an additional tool, Participant 2 responded:

> *I think it would be great as an addition, but I would hate to take the people out of judging, as it [AI] couldn't judge artistry.* (Participant 2)

This was reinforced by Participant 6:

> *There are certainly things that AI could look at, but there are things it would miss. The overall impression [of a dive] for example.* (Participant 6).

Participants were also asked for any areas that they felt AI might help, given consensus that, due to difficulties with artistry, technology could not be employed for analysing and scoring the total dive. Participant 3 noted:

> *Perhaps dangerously close dives could be measured and identified with the help of technology, therefore assisting judges. I wouldn't say no to that.* (Participant 3).

Participant 1 also suggested using laser technology as an additional tool to help with measurements difficult to see with the naked eye:

> *If we agree how many centimetres from the board is acceptable, then they can put the laser in. This I can more imagine than dive by dive analysis.* (Participant 1)

However, most participants, as elaborated in Figure 2, would find some technological innovation to be a great tool to help the decision-making of the judges. Some key elements of diving could be better analysed, though (again) rules and point deduction protocols ought to be clarified by FINA beforehand.

RQ (3) According to divers, coaches, and judges, what is the final desirability of an AI-based scoring system?

Participants agreed on the benefits of technology as an addition. However, issues around the availability and trustworthiness of any technology were raised. This first question about availability was addressed by several participants, most of whom were supportive, but with caveats:

> *I think in this case, it would be good… but not at all the competitions because local and small competitions cannot use it, as the cost would be prohibitive.* (Participant 1).

The issue of availability was a concern with Participant 3, who commented that cost could be a limiting factor, with the impact felt not only in competition, but potentially in training environments:

> *As introduction of laser technology or AI-based programmes will be costly and nations where diving isn't funded or supported as much may be at a disadvantage. This hits competition and training venues.* (Participant 3)

There were some practical issues that also caused concern:

> *I don't know if it would work, but I fear that it would take too long... Especially in diving, we have 50-60 divers, times 6… so it's 300 dives. I don't know if it is sitting minutes and hours to analyse it.* (Participant 1)

Further concerns about practicality considered the divers, coaches, and spectators:

> *The trouble with diving is that people always liked the scoring system. The public… because it was so quick compared to gymnastics and ice-skating. (Participant 5)*

Suggestions were mooted that competitions would lose a valued cultural atmosphere if judges were not in attendance. Participant 2 vocalised this sentiment:

> *In my opinion, I think that would be great to have in addition. But I don't think… there is just something nice about the judges being there and seeing the real thing going on. (Participant 2)*

Worries were also expressed about losing the individual nature of diving if AI took over:

> *You know, I feel not quite resistant [to the introduction of AI], but I am slightly reluctant to introduce something like this because… then I feel like it is homogenising the sport as well. (Participant 6)*

But there was positivity:

> *I mean, during the pandemic, tennis used no linesmen and used a technology for it. I feel like diving has been a little bit stagnant; we haven't embraced as much technology as we possibly could. (Participant 4)*

DISCUSSION

There is a need for domain-specificity when conceiving perfectionism in sport (Anshel and Eom, 2003; Dunn *et al*., 2005; McArdle, 2010; Haase *et al*., 2013). Sports are different; therefore, the conception is not a "*one-size fits all*". Perfectionism in diving has been found related to athletes' mindsets, as well as scores, according to Olympic divers and judges. Findings suggest that an existing perfect dive is a misconception, due to personality and cultural differences with study participants implying major differences in techniques, from country to country and culture to culture. According to the Olympic gold medallist diver, it is easy to distinguish a Chinese diver's style from a Russian's (a Russian diver "*kicks out differently*"). Such dissimilarities may cause problems when determining the perfect dive and building a computer-based system around that ideal model. Whose ideal model would be selected? Moreover, FINA tries to implement modifications, clarifications, or removal and addition of rules in each FINA cycle (four years), and slight rule changes would be likely to cause extreme difficulties in "*older*" dives. A dive that resulted in a score of 10 from a judge eight years ago would be unlikely to receive the same scores today. And the database does not store previous dives, as the new rules prohibit comparisons. The personal preference of judges, the cultural and technical differences in styles and execution, and the FINA rule changes all suggest the inadequacy of an AI-based scoring system in diving.

Participants implied that the subjectivity of the system does not equal weakness. However, research suggests otherwise. Figure skating has been in the spotlight due to the controversial events at the 2002 Winter Olympic Games (Cheng, 2013; Zitzewitz, 2014; Lom, 2016). The pairs' figure skating event had suspicions of wrongdoings, officials were later suspended, and the scandal led to the introduction of the more objective ISU Judging System (Van Veen, 2012). Consequently, the possibility of organised scandals in artistic sports was heavily reduced.

Further results show the importance of context within judging. Scores are substantially impacted according to whether one is judging, for instance, children, juniors, amateur or elite competitors. According to the participants, the scores are not comparable, as the context of the dive is ineliminable. For example, a dive that receives a 10 is merely the best in *that* competition, with *its* rules and broader context of adjudication. The scores of a dive at Tokyo 2021 (for example) should not be compared to the scores of a dive at Athens 2004.

Other findings are supported by Allen *et al*. (2021). Artistic elements are difficult to judge with computer technology. Participants have revealed that technology might struggle to identify the perfect spin, twist, parabola of the dive or the ideal time spent in the air. These components of a dive are subjectively measured, and it might not be possible to measure them numerically, due to the different techniques, body shapes and styles of divers from different countries. Nevertheless, there are feasible ways to include technology as an addition to traditional judging methods. First, the degree of entry may be measured, and judges could receive a quantitative result, which can ground point deductions, in turn strengthening the objectivity and fairness of results. One participant suggested that judges should be experienced enough and disagreed with the need for technology to measure the degree of entry. However, human errors are inevitable. Therefore, this study supports the introduction of a more accurate technological system to analyse the entry. Second, if a diver's head is dangerously close to the board, the dive should not exceed a score of 2 (Figure 1). Once rules are clarified, technology ought to measure the distance between the platform or springboard and the diver's head at all times during a dive. If the head enters the "*danger zone*", judges should be notified. This technological modernisation is pending, with OMEGA (see www.omegatiming.com), the official timekeeper of the Olympic Games (Featherstone and Tamari, 2019), prioritising safety and fairness. By introducing computer technology to measure the distance between the head and the board/platform, the safety of participants could be ensured. There are other, potentially pioneering OMEGA proposals. A joint recognition software could analyse motion and posture, such as bent knees in pike position or open knees in tuck position. Finally, OMEGA aims to look at the point of entry and horizontal displacement from the board/platform. While investigating the point of entry, joint recognition may be used to compare divers to the ideal model (100% vertical). These steps should be regarded as the first towards the introduction of technology in diving. OMEGA differs from other companies, as their technology offers live metrics with extremely fast information processing (which could enhance fan entertainment). Further tools may be implemented, although current FINA rules and point-deduction descriptions would substantially impact innovations.

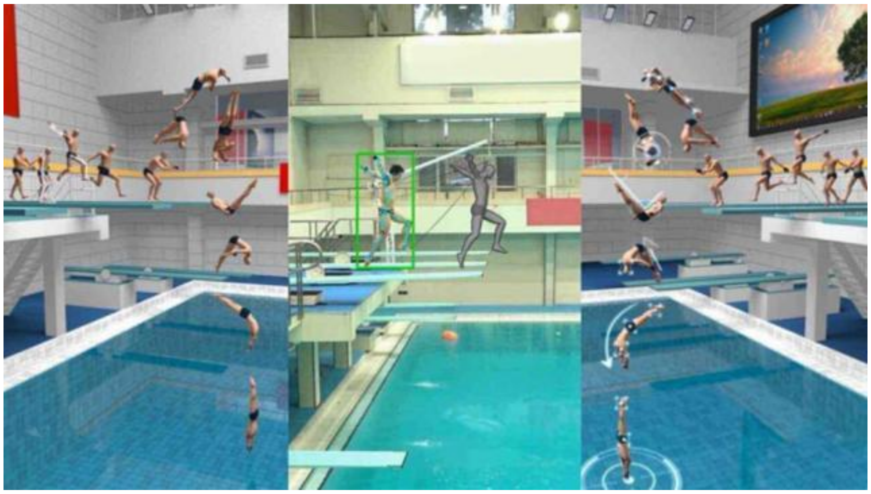

Figure 3. Baidu's AI-based training system (Zhang, 2021).

The innovative technology of Baidu (see www.baidu.com) should also be examined. The giant technology company created a training system to help the national diving team of China (Zhang, 2021). The company's high-speed video provides real-time feedback to coaches about the angle of joints and the posture of divers. Baidu's technology captures in 2D before estimating the posture and the angle of joints in 3D on coaches' tablets (Figure 3). There is currently no relevant literature that explores the advantages and potential of the system. However, it is believed to be used only for training purposes and could not be used for judging yet. Coaches are still required to decide what the perfect motion should look like.

The nearest theoretical idea comes from the concept of Action Quality Assessment (AQA). AQA can assess how well an action is performed. However, complications surface in the context of diving (Kim, 2021) due to the nature of the sport and the complicated point deduction system; capturing motion and pose estimations are not enough. Consequently, Kim (2021) suggested the use of spatiotemporal features, while Parmar and Morris (2019) recommended a multitask learning (MLT) approach to judging a dive. With MLT performing better in capturing the quality of action (Parmar and Morris, 2019) the current authors suggest that it could possibly lead to future innovation in sports where a subjective judging system is used.

While Baidu's training system could be modified and advanced, participants remain against the introduction of a fully automated scoring system. Homogenising the sport would take away the freedom, creativity, and flair of the divers. It would become boring to watch, as every diver would aim for the same robotic routine. This could undermine the popularity of the sport.

The Human factor

Though subjectivity in the scoring system was found to be attractive in ways, issues regarding the "*human factor*" are indisputable. Latimer (2020) explains how the processing of "*complex information in a condensed timeframe*" exceeds human capabilities. Humans make mistakes. In some cases, these are down to limited experience or immense pressure. In other cases, incorrect scores are associated with explicit biases, especially liable where performances are judged on a subjective basis. Such biases have been identified by previous literature (Leskošek *et al*., 2012; Leandro *et al*., 2017; Latimer, 2020). Latimer (2020), again, separates explicit biases into nationalistic and reverse nationalistic. One of the participants (details withheld to assure anonymity) cited the latter, having observed a sudden change in scores after changing nationality. Though the diver has improved, the change of flag next to the name resulted in slightly lower scores in the European and World Championships. Therefore, wrongdoing can be seen, confirming Houston (2022), at even the highest level of diving. FINA has taken the remedial measure of having neutral panels of judges for finals.

Limitations and recommendations for future research

Conception of the perfect routine changes from country to country and culture to culture. Sample size and demographic seems to be this study's greatest limitation. The study did not include divers, coaches, and judges from North or South America, Africa, or Asia. To improve reliability and validity of the findings, future research should include a wider range of countries, which would deepen understanding of the perfect dive and unveil the best way to introduce technology into diving. Investigation of media personnel, equivalent to Allen *et al*.'s (2021) gymnastics investigation, could augment the findings. Finally, when technological tools are investigated, cost-related advantages and disadvantages must be considered. Introducing expensive technology to diving might widen the gap between countries, due to availability or funding. More advanced countries might have a greater advantage in practising with expensive technological devices. Consequently, researchers should consider cost-effective alternatives.

CONCLUSION

A need for innovation has been outlined by participants in this study. Further research and examples from sport (e.g., figure skating in 2002, discussed in Zitzewitz, 2014) also suggest the need to improve the objectivity of the scoring system in artistic sports. AI is yet to measure motion and judge complex movement patterns, as the constantly changing and culture-relative "*perfect*" routine seems difficult to describe. Nevertheless, technology should be used as a tool to assist the judges. Combining the radical proposals of Baidu, OMEGA, and Fujitsu (Fujiwara and Ito, 2018) can lead to the reduction and possible elimination of bias and subjectivity. Issues regarding the current scoring system derive from the uncertain and vague FINA rules. Therefore, the federation must clarify their rules and point deduction system. It must elucidate terms such as "*unsafely*" or "*insufficient*" and assign numerical values to allow computer technology to judge and score dives. Again, the database of dives and their tariffs change over time, meaning investment is needed to ensure that tariffs are updated accordingly. Technology can then be implemented, not to replace but to assist judges. Diving would then not only be fairer but be seen to be fairer.

AUTHOR CONTRIBUTIONS

Conceptualisation of project: Simon Jakab, Paul Davis. Literature review (including write-up): Simon Jakab, Paul Davis. Data collection: Simon Jakab. Data analysis: Simon Jakab, Ian Whyte. Write-up: Simon Jakab, Paul Davis, Ian Whyte. Editing: all authors.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

The impact of velocity-based movement on electromyography activity in standard lower-limb strength exercises

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ABSTRACT

Previous research has shown that the velocity of movement can influence muscle activation. However, no studies have investigated the impact of movement velocity under the same load conditions on electromyography (EMG) activity in knee and hip extensors. This study aims to compare the mean muscle activation of gluteus maximus [GM], biceps femoris [BF], semitendinosus [ST] and rectus femoris [RF] in three hip extension exercises (i.e., squat [SQ], hip thrust [HT] and Bulgarian squat [BS]) with two different movement velocities (i.e., maximum velocity [MV] and controlled velocity [CV]). Fifteen physically active students participated. The mean EMG activity of all targeted muscles was measured. Maximum Voluntary Isometric Contraction was used to normalize EMG muscle activation. All muscles were activated to a greater extent in BS at MV than in the same exercise performed at CV. However, during the SQ exercise, EMG differences between velocities were only obtained for BF and GM, and in HT, only for GM ($p < .05$). In conclusion, higher velocity involves higher activation of the lower-limb muscles, depending on the physical test, and this can be used to better plan the functional recovery of injury, taking it into consideration for intensity progression and avoiding the risks of overly strenuous exercises.

Keywords: Sport medicine, Maximum velocity, Strengthening exercise, Hamstring injury prevention.

Cite this article as:
Ferri-Caruana, A., Muñoz-Gómez, E., Mollà-Casanova, S., Camarón-Mallén, P., & Serra-Añó, P. (2023). The impact of velocity-based movement on electromyography activity in standard lower-limb strength exercises. *Scientific Journal of Sport and Performance*, *2*(3), 314-325. https://doi.org/10.55860/MXQO3997

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Submitted for publication May 09, 2023.
Accepted for publication June 05, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/MXQO3997

INTRODUCTION

Resistance training is very important in sports performance, injury prevention and rehabilitation (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Bourne et al., 2018; Buckthorpe & Roi, 2017; Ferri Caruana et al., 2020). Previous research has shown that several uncontrollable factors (i.e., muscle size and length, joint angle, myotatic reflex and muscle elasticity (Cronin et al., 2008; Kuriki et al., 2012; Watanabe & Akima, 2011)) and controllable factors (i.e., exercise intensity (Keogh et al., 1999), the velocity of movement (Sakamoto & Sinclair, 2012), fatigue (Sakamoto & Sinclair, 2012), mental focus (Snyder & Fry, 2012), movement phases (van den Tillaar et al., 2012) and stability conditions) may affect the degree of muscle activation in dynamic contractions. Therefore, in order to control exercise performance, it is important to understand the impact of each of these controllable factors on muscle activation since they are the key improving training efficiency (Stastny et al., 2017).

Although the effect of most of the controllable factors, such as exercise load, fatigue, mental focus, movement phases and stability condition, has been widely studied (Cochrane & Barnes, 2015; Hassani et al., 2006; Krzysztofik et al., 2019; Pincivero et al., 2006; Smilios et al., 2010; van den Tillaar et al., 2019; van den Tillaar & Sousa, 2019), there is controversy in research about the effect of movement velocity on muscle activation. Physiologically, a rapid contraction produces rapid recruitment of motor units (Farina et al., 2004; Felici, 2006), reduces the required time for cross-bridge formations (Jones et al., 2004), increases the velocity of movement (Carpentier et al., 1996; Enoka, 2008) and decreases the fatigue resistance of fast-twitch motor units which are preferentially recruited in dynamic actions (Hunter et al., 2005). All of this could reflect higher muscle electromyography (EMG) activity (Jakobsen et al., 2013; Tsoukos et al., 2021) regardless of the load applied (Sakamoto & Sinclair, 2012; van den Tillaar et al., 2019).

In this line, only three studies compared different exercise velocities using the same load. Calatayud *et al.* (Calatayud et al., 2018) found that in the bench press exercise and using 50% 1-repetition maximum (1-RM) of load, maximum EMG activity of the pectoralis major and the triceps brachii muscles was higher when movement was performed at maximum velocity (MV) compared to a controlled movement velocity (CV). In the same way, Sakamoto *et al.* (Sakamoto & Sinclair, 2012) concluded that EMG amplitudes were greater under faster and heavier bench press conditions.

In contrast, Gentil *et al.* (Gentil et al., 2017) examined the effects of movement velocity on muscle EMG activity during a no-load resistance training exercise and they did not find higher EMG activity during higher velocities compared to slower velocities. However, study participants were asked to sustain maximum contraction during the full range of motion, without any external load, therefore the transferability of results to the clinical or sports performance setting is difficult.

Besides these controllable factors that have an effect on performance, it is further essential to select exercises suited to the goal set, for example, avoiding those too physically demanding that may jeopardize healing program goals. Hip extension is the most trained movement, since it is important for accelerating the body's upward and forward movement such as during sprinting and jumping (Neumann, 2010). In this regard, the squat (SQ) (Clark et al., 2012), Bulgarian squat (BS) (Appleby et al., 2019), and hip thrust (HT) (Contreras et al., 2015, 2017) are often used in training to increase force production during hip extension, since these exercises produce high activation in lower key limb muscles (i.e., rectus femoris [RF], biceps femoris [BF], gluteus maximus [GM] and semitendinosus [ST]). However, no studies have compared muscle activation using different movement velocities in regular hip exercises.

Taking into account what has been discussed above, this study aimed to compare the mean muscle activation of the GM, BF, ST and RF in three hip extension exercises (i.e., SQ, BS and HT) using two different movement speeds: MV (maximum velocity) and CV (controlled velocity).

METHODS

Study design

This cross-sectional study compares the mean EMG activity of different lower-limb muscles (i.e., RF, BF, ST and GM) normalized by Maximum Voluntary Isometric Contraction (MVIC) during three resistance exercises (i.e., SQ, HT and BS) at two different movement velocities: MV and CV.

Participants

Healthy active University students were recruited. Inclusion criteria were i. aged 18 years or older; and ii. regular resistance training (> 3 h per week). Exclusion criteria were i. a history of lower-limb or low back injury in the 6 months before the study, ii. any acute or chronic pain in the lower body or low back, iii. neurological or vestibular disease, and iv. any contraindication for exercise. Moreover, participants were asked to refrain from caffeine intake and any unaccustomed or intensive exercise during the 72 h before the assessment sessions.

Procedures

The study was carried out following the guidelines contained in the Declaration of Helsinki and was approved by the University of Valencia Research Ethics Committee (1552264). All eligible candidates who agreed to take part in the study provided written informed consent.

During the week before measurements, participants were assessed for anthropometric parameters (i.e., body mass and height), and they were familiarized with all exercises (Supplementary Material). In this session, participants were instructed to use the proper technique throughout the exercises, and the pace of the exercise was also practiced before assessment and controlled using a metronome. The exercises were chosen based on existing scientific research to ensure lower-limb training (Appleby et al., 2019; Neumann, 2010).

The second visit was a 60-minute testing session. It began following a 10-min warm-up protocol involving dynamic stretching, jogging, double leg squats and jumping exercises. Then, MVIC from each muscle was obtained. The dominant (preferred kicking) limb was selected for data collection.

For MVIC, two 5-s maximum contractions with 1-minute resting intervals between trials were performed, and the highest mean EMG activity over 5 seconds was recorded as the MVIC. The MVIC test for knee flexors (i.e., BF and ST) was performed with participants lying in the prone position with their knees flexed 45º. Manual resistance was then applied at the ankle as the volunteer attempted to flex the knee. In addition, the MVIC for GM was taken with the subjects in a prone position and their knee flexed 90º. In this position, the subject was stabilized holding the uninvolved leg and the upper body and manual resistance was placed at the distal part of the femur, while the volunteer performed a hip extension. Finally, the MVIC for RF was taken with the subject on a quad extension machine, with the hip and torso firmly against the seat, 90º knee angle and a strap around the foot providing the fixed resistance, while the volunteer performed a knee extension.

After 3 minutes rest, exercises were carried out in a pre-established order: SQ (as bilateral and multiarticular exercise), HT (as bilateral and hip-dominant exercise) and BS (as unilateral exercise). However, the order of exercise methods (i.e., CV and MV) was randomized using the simple randomization method according to https://www.randomizer.org/. At the end of each exercise, a 3-min rest was taken to allow full recovery.

Finally, the mean EMG activation of the GM, BF, ST and RF were recorded using the MVIC method for normalizing EMG data (in percentage).

Description of strength training methods and velocities

Training procedures are shown in the Supplementary Material. For the SQ, HT and BS at CV, 1 series of 6 repetitions was performed using a metronome to guide the pace (3 s during the eccentric phase, 1 s during the isometric phase, and 2 s during the concentric phase with a constant velocity) (Calatayud et al., 2018). For SQ, HT and BS conducted at MV, volunteers were asked to do 1 set of 4 repetitions at a faster velocity (1 s during the eccentric phase, 1 s during the isometric phase and maximum velocity during the concentric phase). The number of repetitions was chosen in accordance with the type of training and time under tension commonly performed in a regular resistance training session (Baechle & Earle, 2008).

A 20-kg barbell and discs with various weights were used to adjust the load for each subject. The weight used in each exercise (the same for both methods) was obtained by calculating 60% of the 1-RM (Castillo et al., 2012). The 1-RM of each subject was estimated using the Vitruve Teams App (version 1.11.2) at the end of the warm-up session. Subjects performed 10 repetitions of each of the exercises at maximum velocity with two loads: 40 kg and 60 kg. Rest periods were 2 min between warm-up sets. Load-velocity profiles and validity of 1-RM prediction methods in different exercises using the Vitruve linear position transducer have been proven reliable (Kilgallon et al., 2022; Pérez-Castilla et al., 2019).

Instrumentation

The mean muscle activation of GM, BF, ST and RF were monitored through surface EMG. For registering EMG signal, the skin was shaved, rubbed, and cleaned with alcohol. Electrodes were placed in pairs 1.5-2 cm apart and parallel to the muscle fibres. Electrode placement was according to SENIAM guidelines (Hermens et al., 1999). To ensure identical positioning of the electrodes, all EMG data were collected in a single session.

The EMG activity was recorded with two portable two-channel devices from the Shimmer group (Realtime Technologies Ltd, Dublin, Ireland) with a 16-bit analogue/digital (A/D) conversion. The sampling frequency was programmed at 1024 Hz. Moreover, during registration, the EMG signal was monitored using the mDurance software (MDurance Solutions S.L., Granada Spain) for Android and stored in a cloud server for further analysis. The application was installed on a ZTE BLADE device, model A506 with the Android 6.0.1 Marshmallow operating system (ZTE Corporation., Shenzhen, China).

A high-pass 20 Hz filter was used (De Luca et al., 2010) and the root mean square (RMS) was calculated from a window showing the duration of test execution and both movement phases were used for the analysis (i.e., concentric and eccentric). To obtain the EMG average, the four middle repetitions for each exercise at CV were used, while all the four repetitions of exercises at MV were used.

Further, to collect hip motion data, a sensor was placed in the middle of the thigh, 5 cm distal to the electrodes of the RF and in line with the patella. Hip range of motion was used to ensure that the SQ and the HT were performed at a similar range of motion through instant feedback to the researcher (5-10º) and to delimit duration of movement.

In order to compare values of different muscle activation patterns, EMG data were normalized as a percentage of the EMG signal recorded during MVIC tests as explained above.

Statistical analysis

Statistical data analysis was conducted using SPSS v26 (Inc. IBM., Chicago, IL, USA). Data were presented as mean and standard deviation (SD). A Repeated Measures T-test with the within-subjects factor 'training method' was used to search for differences between the two training methods (i.e., MV and CV) in the mean EMG activity of the key muscles (i.e., GM, BF, ST and RF). Type I error was set at 5% ($p \leq .05$).

RESULTS

Fifteen physically active University students (5 females and 10 males) participated in this study. Demographic data are shown in Table 1.

Table 1. Demographic data.

	Age (years)	Height (metres)	Weight (kilogrammes)
Men	21.20 (0.63)	1.80 (0.08)	75.75 (9.90)
Women	20.20 (1.64)	1.65 (0.09)	62.00 (13.56)
Total	20.87 (1.13)	1.75 (0.11)	71.17 (12.67)

Note. Data are expressed in mean (standard deviation).

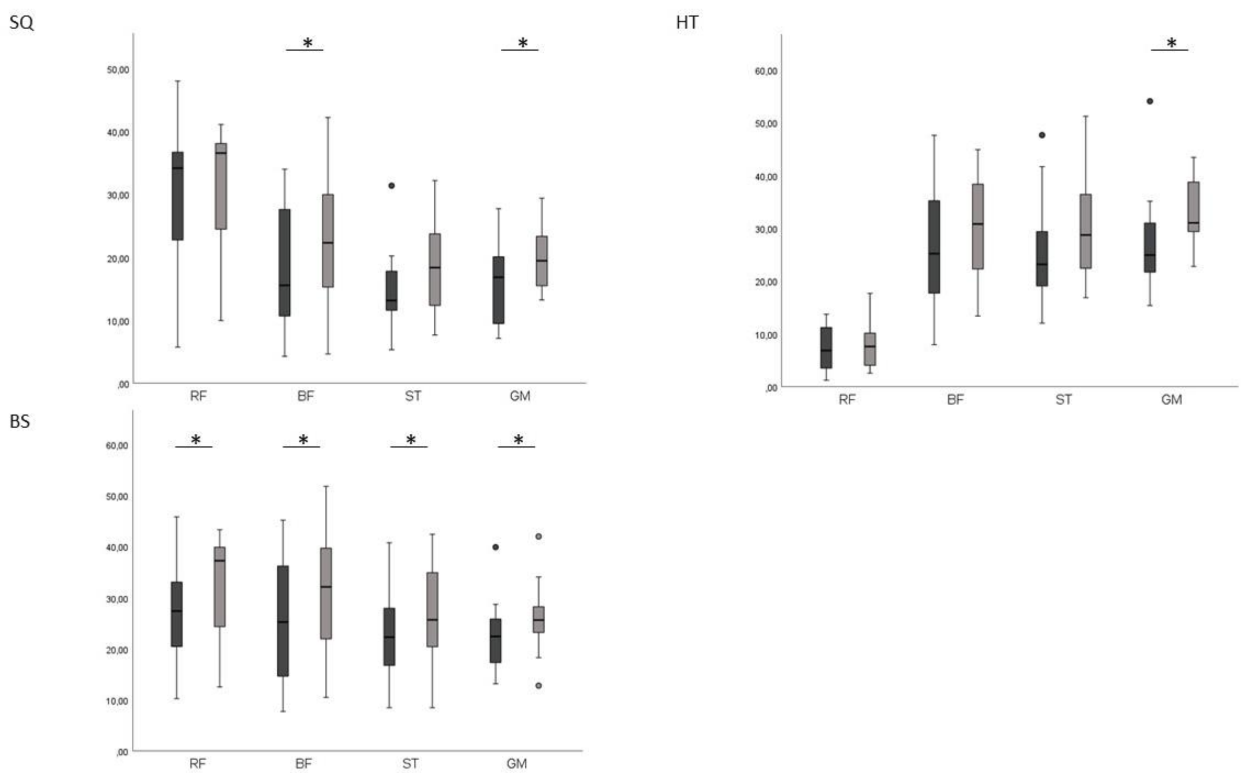

Figure 1. Comparison of mean EMG activity of the RF, BF, ST and GM muscles for SQ, HT and BS exercises using CV (dark bars) and MV (light bars).

Results of mean EMG activity in each muscle are shown in Figure 1. BF and GM obtained significantly higher values at MV compared to CV in SQ exercise, but ST and RF showed no differences between movement velocities in this exercise. With regard to HT, only GM showed significantly higher mean EMG activity at MV; for the other muscles there were no differences between movement velocities. For BS, all muscles exhibited significantly higher EMG activity at MV compared to CV.

DISCUSSION

This is the first study to analyse EMG activity of the knee flexor and hip extensor muscles (i.e., RF, BF, ST and GM) during SQ, HT and BS exercises using two velocities (i.e., MV and CV). We investigated whether the increased velocity is enough to improve EMG activity of the muscles and thus avoid high-load strength training that has been related to injuries (Keogh & Winwood, 2017). Overall, significantly higher mean EMG activity was found at MV compared to CV for all muscles assessed except for RF.

Previous studies that assess the bench press exercise similarly compared different velocities (e.g., Sakamoto *et al.*(Sakamoto & Sinclair, 2012) compare slow 5.6 s/repetition, medium 2.8 s/repetition, fast 1.9 s/repetition, and MV; and Calatayud *et al.* and Gentil *et al.*(Calatayud et al., 2018; Gentil et al., 2017) compared CV vs MV), using the same load for each velocity. Their results were not consistent since not all muscles exhibited an increase in EMG amplitude when faster velocities were used to perform the exercises. Calatayud *et al.* and Sakamoto *et al.* (Calatayud et al., 2018; Sakamoto & Sinclair, 2012) reported higher EMG activity for the pectoralis major, deltoid and triceps brachii muscles when higher speed was used, while Gentil *et al.* found no differences between movement velocities for the biceps and triceps brachii (Gentil et al., 2017). Despite this controversy, earlier literature using other tools to assess differences between movement velocities in terms of muscle response (i.e., hypertrophy, strength, tensiomyography and other physiological parameters) supports that MV movements exhibit higher hormonal and neurological responses (Kojić et al., 2021; Pryor et al., 2011; Wilk et al., 2018), while muscles are subject to a greater work load (Cormie et al., 2009, 2010), as compared to lower movement velocities.

In this study, the average (minimum and maximum) increment in EMG activity when performing the exercises at MV was 17.41% (1.08%-25.49%) compared to CV. Although not entirely comparable, these values are slightly higher than those reported by Calatayud *et al.* (Calatayud et al., 2019), which showed increments of EMG activity when performing the bench press exercise at MV of about 9% for the pectoralis major and 14% for the triceps brachii. This difference might be because they used a lower load (i.e., 50% 1-RM load compared to 60% 1-RM in our study). In the same line, Sakamoto *et al.* (Sakamoto & Sinclair, 2012) found an overall increment of EMG activity (around 20%) similar to our study when high velocity of movement was used for pectoralis major, triceps brachii and anterior deltoid exercises with a 60% 1-RM load.

When comparing muscle activation between velocities (i.e., MV or CV), in each of the exercises, SQ rendered a higher mean increment of EMG activity for BF and GM at MV. A rapid contraction produces higher muscle EMG activity through faster recruitment of motor units (Farina et al., 2004; Felici, 2006), decreasing the required time for cross-bridge formations (Jones et al., 2004) and fast-twitch motor units (Hunter et al., 2005), and increasing velocity of movement (Carpentier et al., 1996; Enoka, 2008). These results suggest that most of the main muscles involved in exercise performance significantly increase their activation when higher speeds are applied to the execution of the movement (i.e., BF and GM) (McCaw & Melrose, 1999).

Conversely, our results failed to report higher EMG activity during MV compared to CV in the SQ exercise for ST and RF, despite the major role of the latter muscle (McCaw & Melrose, 1999) . RF has a particular architecture, specifically its proportion of active type I and II fibres and its pennate architecture. On the one hand, RF has a higher proportion of fast-twitch muscle fibres and a lower proportion of slow-twitch muscle fibres compared to GM, ST and BF (Punkt, 2012). Accordingly, this muscle is more prepared to perform faster dynamic movements, without the need of increasing the EMG activity. On the other hand, when a pennate muscle, like RF, contracts and shortens, the penetration angle increases, allowing higher velocities without needing to increase muscle activity (Azizi et al., 2008).

Regarding the lack of significant differences between velocities in ST, it should be noted that ST has a more important intervention in single-limb SQ performance, as compared to double-limb SQ. During single-limb performance, less external hip rotation and greater knee abduction were recorded due to the repositioning of the body weight (Khuu et al., 2016). In this way, previous studies (McCurdy et al., 2018; Monajati et al., 2019) reported higher muscle activation of ST during the single-leg squat compared to the double-leg squat, while BF remains at a similar level of activation. Therefore, to better assess differences between velocities in this muscle, single-leg squat would be more appropriate, such as using the BS exercise.

For HT, only the GM muscle showed a significantly higher activation at MV compared to CV. In this case, MV produced higher EMG activation of those muscles most involved in the exercise performed; previous studies have shown that GM has a major role in the HT exercise execution, far more important than the role of other muscles involved (García et al., 2020; Neto et al., 2019). This main contribution is probably because HT produces greater bilateral extensor demand at the hip joint in comparison to the knee joint (Brazil et al., 2021) and, therefore, hip extensor muscles involving the knee joint (i.e., BF and ST) are activated to a smaller extent. In this way, the use of higher velocities may place a higher demand on the GM during the exercise, improving its EMG activation capacity with low loads, making this a feasible option for the recovery or prevention of hip injuries. Indeed, HT could be an ideal exercise for untrained people because it is a guided close-chain exercise, preventing unwanted movements, even at high velocities.

With regard to the BS exercise, higher mean EMG activity was registered at MV for all muscles. This single-leg squat exercise has shown to produce higher neuromuscular activation in both hamstring and quadriceps muscles as compared to other types of squats (i.e., double-leg squat and double-leg squat with Bosu) (Monajati et al., 2019) at a slow velocity. As with the HT exercise, the use of fast speeds during the performance of BS promoted higher EMG activity of the main muscles involved in execution (i.e., all assessed muscles). Thus, BS at MV could be useful to increase muscle activation in trained people, but further studies are needed to establish how higher speeds during BS may affect muscle activation in untrained people lacking the training skills of the former.

Overall, the findings suggest that the greater the difficulty or instability of the exercise, (i.e., BS) the higher the increase in muscle activation at high speeds for all the muscles involved.

There were some limitations in this study since all participants were active healthy individuals; thus, our results cannot be extrapolated to the sedentary population. Moreover, activation strategies not only vary among individuals but are unique to each individual (Hug et al., 2010). Our results support this idea based on the large standard deviations obtained. Accordingly, individual differences must be accounted for when setting SQ, HT and BS workout routines at MV or CV.

CONCLUSION

This study supports that standard lower-limb exercises performed at MV generally achieve higher muscle activation compared to their CV performance using the same load. Larger increments were obtained in the more physically demanding exercises.

Therefore, SQ, HT and BF at MV could be an ideal option for achieving higher muscle activation of BF, ST and GM, while avoiding the risks of high-intensity training.

AUTHOR CONTRIBUTIONS

Pilar Serra-Añó: conceptualization, data analysis, supervision, final article revision, and project administration. Ana Ferri-Caruana, Sara Mollà-Casanova, Elena Muñoz-Gómez: methodology, data analysis and article redaction. Pablo Camarón-Mallén: assessments and data acquisition.

SUPPORTING AGENCIES

This work was partially supported by Grants from the Spanish Government (PID2021-125694OB-I00; co-financed by EU FEDER funds;), Generalitat Valenciana, Conselleria d'Innovació, Universitats, Ciència i Societat (CIAICO/2021/215); and from Universitat de València (INV19-01-13-07).

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

We would like to thank all the subjects who selflessly participated in the study and to Ilustre Colegio Oficial de Fisioterapeutas de la CV.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

REVIEW ARTICLE

The effectiveness of long-term physical rehabilitation to improve balance and locomotion in older people with Parkinson's disease: A systematic review

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ABSTRACT

Walking and balance alterations are critical to address in older adults living with Parkinson's Disease (PD). These alterations negatively impact activities of daily life, decrease the quality of life and increase the risk of falls. Objective: Analyse the effectiveness of different long-term exercise interventions to improve walking and balance parameters in people aged over 60 years with PD. Methods: Experimental studies from the last 10 years collected from 5 databases (PEDro, PubMed, WOS and EBSCO) were analysed. PEDro scale was used to analyse the quality of the studies, and the result shown in the studies was contrasted with the minimal detectable change (MDC). Results: From 413 studies, a total of 7 RCTs and 2 pilot studies were included in the analysis. The range of age was 65.8 ± 10.7 and 73.59 ± 7.93 years. The duration of the disease was 5 to 15 years. The methodological quality ranged from "*good*" to "*excellent*". Conclusions: More significant clinical effect in PD population was obtained after interventions that included: high-intensity strength training, progressive increase of resistance, aerobic exercise, and walking and balance training.
Keywords: Parkinson’s disease, Exercise therapy, Rehabilitation, Elderly, Gait.

Cite this article as:
Silva Cárdenas, J., Velásquez Chávez, N., Rosas Ruiz, M., Vargas Vega, S., & Fritz Silva, N. B. (2023). The effectiveness of long-term physical rehabilitation to improve balance and locomotion in older people with Parkinson's disease: A systematic review. *Scientific Journal of Sport and Performance*, *2*(3), 326-338. https://doi.org/10.55860/ULGA8396

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Submitted for publication May 11, 2023.
Accepted for publication June 05, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/ULGA8396

INTRODUCTION

Parkinson's disease (PD) is a chronic neurodegenerative disease. PD is characterized by loss of neurons in the Substantia Nigra pars compacta (SNc) and decreased dopamine levels in the entire nervous system. Four clinical signs can appear during the progression of PD: bradykinesia, tremor, rigidity and weak postural control.

Ageing is an essential factor in developing PD. Between 1995 and 2015, the number of PD cases rose to 6 million globally. People living with PD are expected to double, reaching 12 million cases by 2040. PD is a neurodegenerative disease with a prominent increase in the number of cases, surpassing Alzheimer's disease. Consequently, the increase in the number of patients contributes to an increasing disease burden on the healthcare system of a country.

People living with PD experience alterations in walking and maintaining balance. These alterations can lead to difficulty performing daily activities, decreased quality of life, and increased risk of falling. In addition, an increased risk of falling can generate fear of walking in some patients. Gazibara et al. 2015, showed after a 20-year follow-up that 81% of the participants with PD had at least one fall in that period. Of the 81% that suffered a fall, 23% had a fracture from the fall.

The execution or planning of multiple tasks can worsen the ability to walk and balance in people with PD. For example, talking or counting backwards while walking can decrease walking velocity in people with PD. Moreover, in the advanced stages of PD, some people develop a "*freeze of gait*", in which the body stops movement in the middle of the walk. Freeze of gait can happen at the beginning of the walk, while walking on narrow paths, turning, or while executing a second task.

Levodopa is one of the main pharmacological treatments for PD. Levodopa's primary purpose is to increase or replace the dopamine in the central nervous system, helping improve the clinical symptoms of PD. In addition to pharmacological treatment, people living with PD often receive exercise-based treatment to improve or maintain physical capacities. The goal of exercise interventions is to improve balance, strength, coordination, walking and postural control capacities. Nevertheless, the effectiveness of exercise interventions needs to be researched.

Together with exercise interventions, new approaches have arisen to solve the rehabilitation problem of people with PD. These approaches include music therapy, yoga, virtual reality, Tai chi and dance. Despite this, owing to the progressive nature of PD, pharmacological treatment seems to be the most effective and lost-lasting approach. However, people can exhibit walking and balance alterations even with proper doses of Levodopa. The objective of this systematic review is to evaluate the long term effectiveness of exercise-based interventions in improving walking and balance in people living with PD over the age of 60 years.

METHODS

This review follows the standards of PRISMA declaration for standards and transparent systematics reviews (Page et al., 2021).

Eligibility criteria

Papers between the years 2012 and 2022 with English as the main language. The inclusion and exclusion criteria are listed in Table 1.

Table 1. Study eligibility criteria.

	Inclusion criteria	Exclusion criteria
P Population	People≥ 60 years old of any gender. PD diagnosis is classified on the HY Scale in stages 1 to 3.	People in advanced stages of PD (stages 4 and 5). People with a diagnosis of PD and other neurological diseases. Included within the same intervention group were people aged 59 or less.
I Intervention	Physical therapy longer than 12 weeks (physiotherapy, physical/therapeutic exercise or other related treatment). Prescription of the intervention in terms of dosage (e.g. frequency, intensity, time, modality). Exercise therapy including the main intervention and other complementary interventions.	There are no details of the intervention procedure. The intervention includes surgical or other treatments not related to exercise.
C Comparison	Inclusion of a passive control group that was intervened by educational sessions or a control group without intervention. An active control group with rehabilitation interventions that do not alter their routine treatment.	Randomised group, without any kind of intervention.
O Outcome	The protocol of the study includes the evaluation of balance and walking with clinical tools commonly used in people with PD (e.g. UPDRS, Berg's Scale, TUG, etc.)	The protocol does not include the evaluation of balance and walking.
D Design	Experimental studies or clinical trials, with or without randomisation.	Systematic reviews, pilot studies, descriptive studies, case and series reports, conference proceedings, and not concluded studies.

Abbreviations: P = Population, I = Intervention, C = Comparison, O = Outcome and D = Desing. PD = Parkinson's disease, HY = Hoehn y Yahr, UPDRS = Unified Parkinson's Disease Rating Scale, TUG = Time Up and Go.

Information sources

The search for articles was performed in electronic databases like EBSCO (MEDLINE, Rehabilitation & Sports Medicine Source, SPORT Discus), Physiotherapy Evidence Database (PEDro), PubMed and Web of Science (WoS) that were available in the Universidad de Los Lagos electronic system. If an article was not available in the system, the researcher asked via email for the paper's authors.

Search strategy

The Medical Subject Heading (MESH) terms related to PD, rehabilitation, balance and walking were used to search for articles. Other related terms were used to increase the accuracy of the search. These terms are listed in Table 2. Boolean operators like AND and OR were also used. The complete strategy is listed below.

Table 2. Controlled and not controlled terms used to develop the search of articles.

	MESH Terms	Optional terms
Patient/Population	Parkinson Disease, Parkinsonian Disorders, Aged, Frail Elderly	Parkinson, Parkinsonism, Parkinson's disease Older adults, elderly, seniors, geriatrics
Intervention	Rehabilitation Medicine, Exercise Intervention, Physical Therapy	Exercise Program
Outcomes	Gait, Walking, Locomotion, Postural Balance	Ambulation

- EBSCO: AB (Parkinson Disease OR Parkinsonian Disorders OR Parkinson OR Parkinsonism OR Parkinson's disease) AND AB (Rehabilitation Medicine OR Exercise Intervention OR Physical Therapy) AND TX (Gait OR Walking Locomotion OR Postural Balance OR Ambulation.
- PEDro: Parkinson Disease, Parkinsonian Disorders.
- PubMed: (((Parkinson Disease [Title/Abstract] OR Parkinsonian Disorders[Title/Abstract] OR Parkinson[Title/Abstract] OR Parkinsonism[Title/Abstract] OR Parkinson's disease[Title/Abstract]) AND (Aged[Title/Abstract] OR Frail Elderly[Title/Abstract] OR Older adults[Title/Abstract] OR elderly seniors[Title/Abstract] OR geriatrics[Title/Abstract])) AND (Rehabilitation Medicine[Title/Abstract] OR Exercise Intervention [Title/Abstract] OR Physical Therapy[Title/Abstract] OR Exercise Program[Title/Abstract])) AND (Gait[Title/Abstract] OR Walking[Title/Abstract] OR Locomotion[Title/Abstract] OR Postural Balance[Title/Abstract] OR Ambulation[Title/Abstract]).
- WOS: Parkinson Disease OR Parkinsonian Disorders OR Parkinson OR Parkinsonism OR Parkinson's disease (Abstract) and Aged OR Frail Elderly OR Older adults OR elderly OR seniors OR geriatrics (Abstract) and Rehabilitation Medicine OR Exercise Intervention OR Physical Therapy OR Exercise Program (Abstract) and Gait OR Walking OR Locomotion OR Postural Balance OR Ambulation (Abstract).

The process of article selection

Four researchers (S.V, J.S, M.R, N.V) developed an independent search of articles in a specific electronic database (each in one database). After the obtention of articles, each researcher swapped their database with another researcher and searched articles again. The previous step was implemented to ensure the obtention of the same results. An extra step was carried out if there were articles that generated doubt or conflict among the researchers. A fifth researcher was in charge of deciding on these articles. The fifth researcher (N.F) is experienced in the field.

Data collection

The principal outcome was obtained from the result of each of the articles previously selected. The change in balance and walking were evaluated in a pre and post-intervention state. The results of the papers were based on a clinical scale or tool: Unified Parkinson's Disease Scale (UPDRS), 10-metre walk test (10MWT), Berg Balance Scale (BBS), the Activities-specific Balance Confidence (ABC) Scale, forward and backwards functional reach (FBFR), Romberg Test (RT), Sharpened Romberg Test (SRT), the Six-Minute Walk Test (6MWT), the Timed "*Up & Go*" Test (TUG), and other similar tests were used by the authors of the selected papers.

Risk of bias assessment

The PEDro scale (Maher et al., 2003) was used to measure the quality of each article included in this systematic review. An analysis of the quality of the internal validity and the presentation of the statistical analysis of each research/clinical trial was performed. According to the PEDro scale, the articles that obtain 9-10 points are considered "*excellent quality*", 6-8 points are considered "*good quality*", 4-5 points are considered "*fair*", and under 4 points are considered "*poor quality*". The articles included in this revision obtained 6 or more points. This threshold was implemented to secure the quality of this review.

Synthesis methods

After selecting articles, the characteristics of each article were summarised in a table. Then, in a second table the details of intervention protocol from each article were plotted. The principal details were type of exercise, time, frequency and duration of the exercises in the protocols. Also the results of balance and walking were added. Finally, the post-intervention values of each article were analysed using the Minimal Detectable Change (MDC) published by Steffen and Seney (2008) for people with PD.

RESULTS

Article selection

The database search yielded 413 results. After removing duplicated studies, a total of 316 were obtained. In 53 cases, the full-text article could not be obtained either through emailing the authors or because it was not part of the Universidad de Los Lagos electronic library. Therefore, the exclusion criteria was applied to the remaining 310 studies.

A total of 304 studies were excluded. The main reason for exclusion was the age of people with PD included in the studies (65 studies). Other reasons to exclude: the stage of PD (n = 20), the intervention was not based on exercise (n = 105), review articles (n = 52), less than 12 weeks of intervention (n = 56) and language (n = 2). After applying the exclusion criteria, four extra articles were added to this analysis. The main reason for this inclusion was that these articles suit the inclusion criteria of age and stage of PD. In total, nine articles were included in this research. The process of selection is explained in the PRISMA flow in Figure 1.

Studies characteristics

Across the nine studies, 297 participants with PD diagnoses were included. Seven randomised clinical trials, two articles that were part of the same research split into two parts (Shen et al., 2014 and Shen et al., 2015), and two were pilot studies (Steffen et al., 2012; Wroblewska et al., 2019). The participants of the study were aged between 64.3 ± 8.25 and 73.59 ± 7.93 years in Shen et al. (2014 and 2015) and Santos et al. (2017). The duration of PD ranged between 5.7 ± 4.23 (Dibble et al., 2015) and 11 ± 6.6 years (Martin et al., 2015). The severity of the disease in the HY scale ranged between 1 and 3. Five studies described the medication of the participants. Levodopa was the primary drug (Dibble et al., 2015; Santos et al., 2017; Shen et al., 2014; Shen et al., 2015; WrTheoblewska et al., 2019). Table 3 contains the details of each article.

Synthesis results

Table 4 includes the analysis of the interventions included in this review. The main results are divided into two categories:

- *Characteristics of the intervention:* Five studies used resistance and strength training as interventions (Dibble et al., 2015; Santos et al., 2017; Paul et al., 2014; Shen et al., 2014; Shen et al., 2015). In five studies, walk training was included in their protocols (Shen et al., 2014; Shen et al., 2015; Shulman et al., 2012; Steffen et al., 2012; Wroblewska et al., 2019). One study used home-based telematic training (Martin et al., 2015). The time of the intervention ranged from 12 weeks (Dibble et al., 2015; Santos et al., 2017; Paul et al., 2014; Shen et al., 2014; Shen et al., 2015; Wroblewska et al., 2019) up to 10 months (Steffen et al., 2012). The frequency of intervention was two times per week, the sessions lasted 30 to 50 minutes on average, but the more common was interventions of more than 60 minutes.

– *The effects of the intervention on walking and balance parameters.* For the evaluation of walk and balance, most of the studies used TUG, UPDRS, 6MWT, 10MWT and the ABC scale. Three studies used the motor scale of the UPDRS to measure changes after the intervention (Dibble et al., 2015; Santos et al., 2017; Steffen et al., 2012), and one study used the mental scale of UPDRS (Steffen et al., 2012). Unfortunately, only one of the three previously mentioned studies achieved positive clinical change in the MDC results (Santos et al., 2017).

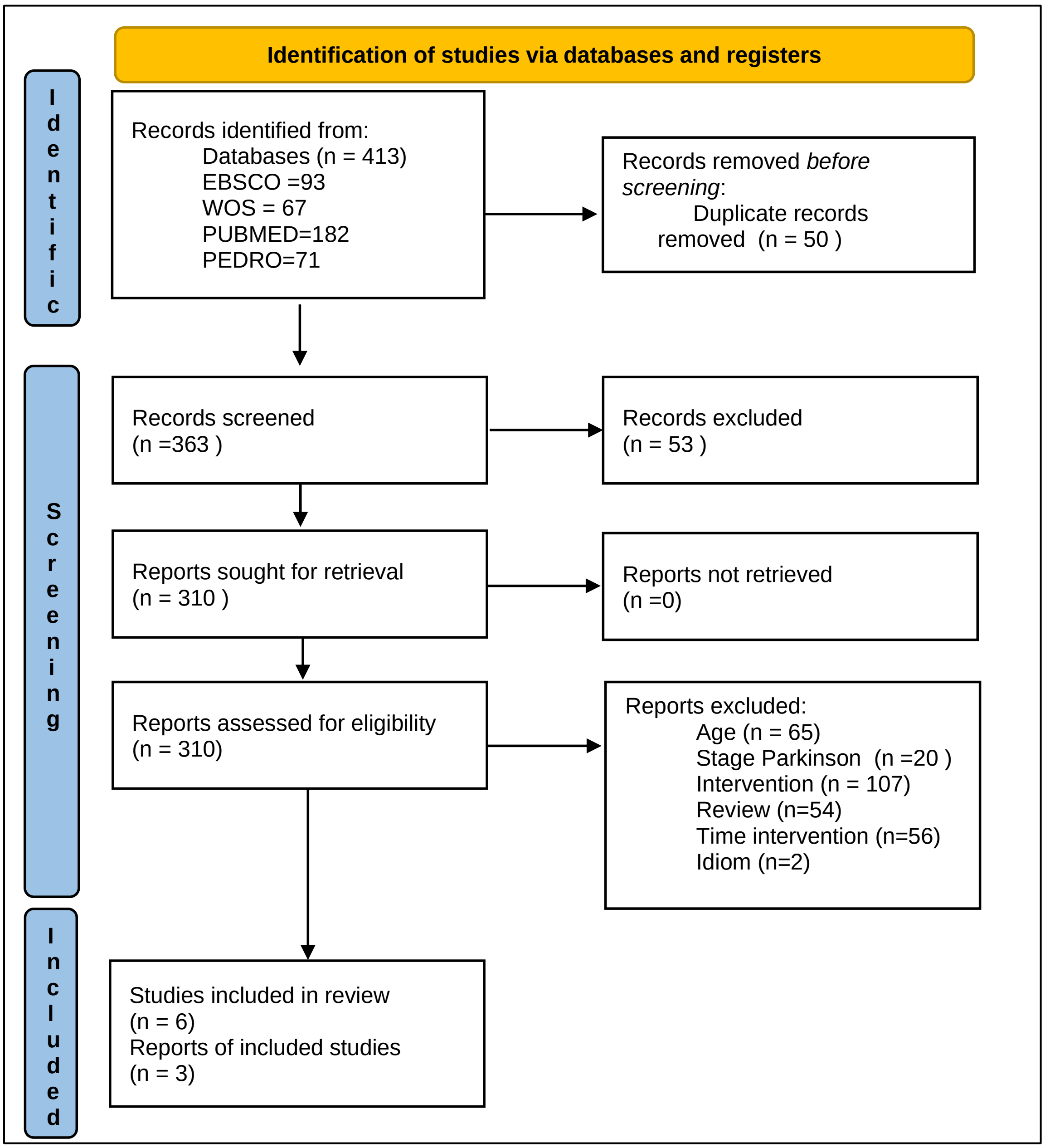

Figure 1. PRISMA flow diagram.

Table 3. Characteristics of the research and population included in this systematic review.

Characteristics of the research			**Study population**					
Author	**Year**	**Design**	**Participants in the study**	**Experimental group (EG)**	**Control group (CG)**	**H&Y stage (mean)**	**Pharmacological treatment**	**Years with PD (mean ± SD)**
Dibble et al.	2015	RCT	n = 41; 25 men and 16 women, average age: 68.4 ± 12.99 years old	n = 20; 11 men and 9 women, average age = 66.00 ± 14.78	***Active control: concentric training*** n = 21; 14 men y 7 women; average age 70.71 ± 9.19	I,II,III y IV average age: 2	Carbidopa/ Levodopa	EG: 8 ± 4.48 CG:5.70 ± 4.23
Martin et al.	2015	RCT	n = 21; 13 men, 8 women; average age=72 ± 5.3 years old	***Immediate start group*** n = 12; 7 men and 5 women; 72 ± 5.1 years old ***Late start group*** n = 9; 6 men and 3 women; 72± 5.8 years old		2.8 ± 0.6	Stable medication, name of the drug not informed	11 ± 6.6
Santos et al.	2017	RCT	n = 28, 15 men, 13 women, average age = 73.59 ± 7.93 years old. ***Active group with exercise practice 3 times per week.***	n = 13; 5 men and 8 women; average age = 73.38 ± 8.81years old	***Active control: usual exercises*** n = 10 men, 5 women, average age 73.80 ± 7.05 years old	EG = 1.92 ± 0.49 CG = 1.86 ± 0.35	Levodopa	GE: 10.84 ± 4.09 GC: 10.46 ± 4.01
Paul et al.	2014	RCT	n = 40; 25 men and 15 women; average age: 66.3 ± 6.5 years old	n = 20, 13 men and 7 women; average = 68.1 ± 5.6 years old	***Active control: Low-intensity exercises*** n = 20, 12 men and 8 women; average age = 64.5 ± 7.6 years old	EG = 2 ± 0.7 CG =1.9 ± 0.9	Does not report information	GE: 7.8 ± 5.2 GC: 7.8 ± 5.9
Shen et al. Shen et al.	2014 2015	RCT RCT	n = 45.35 men and 10 women: average age = 64.3 ± 8.25 years old	***Balance training group*** n = 22, 13 men and 9 women; average age = 63.3 ± 8.0 years	***Strength training control group*** n = 23, 12 men and 11 women; average age = 65.3 ± 8.5 years old	EG 2.4 ± 0.5 CG 2.5 ± 0.5	Levodopa	GE: 8.1 ± 4.3 GC: 6.6 ± 4.0
Shulman et al.	2012	RCT	n = 67; 50 men, 17 women; average age 65.8 ± 10.7 years old	***High-intensity training group*** n = 23; 16 men and 7 women; average age = 66.1 ± 9.7 years old ***Low-intensity training group*** n = 22; n = 22; 16 men and 6 women; average age = 65.8 ± 11.5 years old	***Active control: resistance training and stretches*** n = 22; 18 men and 4 women y average age = 65.3 ± 11.3 years old	I, II III 2 (n = 53) 2.5 (n = 4) 3 (n = 10)	Stable medication, name of the drug not informed	6.2 ± 3.8
Steffen et al.	2012	Pilot Study	n = 15; 12 men; 3 women; average age = 72 ± 8 years old.		Does not apply	3 ± 1	Does not report information	6.0 ± 5
Wroblewska et al.	2019	Pilot Study	n = 40; 17 men and 23 women; average age: 69.8 ± 7.3 years old	n = 20; 8 men and 12 women; average age = 72.1 ± 7.5 years old	***Passive control*** n = 20; 9 men and 11 women; average age = 67.6 ± 6.6 years old	2.5	Levodopa, Ropinirole y and other drugs against PD	6.0 ± 1.2

Abbreviations: RCT = Randomised clinical trial; EG = Experimental group; CG = Control group; SD = Standard deviation.

Table 4. Characteristics of the interventions and effect on gait and ambulation parameters reported in the investigations (*continue on the next page*).

Authors/ Quality	Characteristics of the intervention		Outcomes	Results of the intervention		
	Modality	Duration		UPDRS (points)	Balance and walking	MCD Results
Dibble et al.(2015) PEDro: 9/10	EG = Resistance exercises with negative eccentric work (RENEW) ACG = General strength exercises	60 minutes, 12 weeks, 2 times per week	UPDRS, FGA y TM6m	**Motor** EG-RENEW: pre = 15.05 ± 7.78 post = 12.7 ± 9.30* ACG: pre = 15.43 ± 8.62 and post =13.14 ± 9.88* $^*p < .05$	**FGA (points)** : EG-RENEW pre = 2210 ± 6.77 y post = 23.75 ± 7.00* ; GCA: pre = 21.14 ± 8.27 y post = 21.90 ± 7.89* **6MWT (m/s) :** EG -RENEW: pre = 558.07 ± 182.49 and post: 583.70 ± 181.61* ; ACG: pre = 485.99 ± 158.95 and post = 506.09 ± 192.41* $p < .05$	**UPDRS** (points) EG- RENEW = ↑2.35(unachieved) ACG = ↓2.29 (unachieved) TM6m (m) EG-RENEW = ↑25.63 (unachieved) ACG = ↑20.1 (unachieved)
Martin et al. (2015) PEDro: 7/10	Cued Up! Exercise program and home-base education to avoid Freeze of gait using auditory cues	30 a 60 min, fomenting the practice of exercise everyday	New freeze of gait questionnaire and weekly self-report of falls.	Not applied	**New freeze of gait questionnaire (points)***:* Immediate start group: pre = 15.7 ± 6.3 and post = 14.8 ± 5.0; Late start group: pre = 16.9 ± 4.1 and post = 16 ± 7.7 **Weekly self-report of falls**. Each participant falls at least 2 times during the study. A mean value of 1.22 falls per week. No statistically significant differences between groups.	Does not apply
Paul et al. (2014) PEDro: 9/10	Strength training using equipment with variable pneumatic resistance	45 min, 2 times per week, 12 weeks of training	Muscle strength, 10 MWT (prefer velocity and fast), TUG, reactions, maximal balance, monopodial test and New freeze of gait questionnaire	Not applied	**10 MWT velocity choose by participant(m/s) :** EG: pre = 1.27 ± 0.17 and post = 1.34 ± 0.22; CG: pre = 1.17 ± 0.31 and post = 1.24 ± 0.38. **10 MWT fast velocity (m/s) :** EG: pre = 1.77 ± 0.25 and post = 1.81 ± 0.31 **;** CG: pre = 1.67 ± 0.39 and post = 1.70 ± 0.44 **TUG (cm) :** EG: pre = 9.7 ± 2.3 and post = 8.3 ± 2.4 ; CG: pre = 9.5 ± 2.8 and post = 8.6 ± 4.3 **Reaction (cm):** EG: pre = 37.0 ± 9.5 and post = 35.2 ± 6.2; CG: pre = 34.3 ± 11.0 and post = 37.5 ± 12.9 **Balance maximal range (cm)** EG: pre = 16.7 ± 5.0 and post = 18.4 ± 4.7 ; CG: pre = 14.4 ± 7.2 and post = 15.1 ± 6.0 **Monopodial test (s) :** EG: pre = 12.9 ± 7.2 and post = 16.1 ± 10.3 ; CG: pre = 20.6 ± 17.3 and post = 21.0 ± 17.2 **New freeze of gait questionnaire (puntos)** : EG: pre = 6.0 ± 8.8 and post = 5.8 ± 7.8; CG: pre = 8.0 ± 10.0 and post: 7.4 ± 10.0	**10 MWT chosen velocity** (m/s) EG: 0.07 (unachieved) CG: 0.07 (unachieved) **10 MWT fast velocity** (m/s) EG: 0.04 (unachieved) CG: 0.03 (unachieved) **TUG** (s) EG: 1.4 (unachieved) CG: 0.9 (unachieved)
Santos et al. (2017) PEDro: 9/10	Progressive resistance training	16 training sessions in 8 weeks. 60 a 70 min, 2 times per week of supervised training. Then, 4 weeks of training without supervision	Anthropometric and neuromuscular function evaluations, 10 MWT, FOG-Q,UPDRS, PDQ-39 and Borg Scale	**Motor** EG: pre = 7.61 ± 5.28 and post = 7.07.± 4.59 CG: pre = 7.30 ± 4.53 and post = 8.8 ± 5.74	**FOG-Q (puntos):** GE: pre = 3.84 ± 3.15 y post: 3.46 ± 3.07; GC: pre = 3.61 ± 3.12 y post: 3.26 ± 1.98 **PDQ-39 (puntos)**: GE: pre = 11.16 ± 7.39 y post± 4.58 ± 4.37* ; GC: pre = 5.98 ± 5.06 y post = 10.60 ± 4.38 **10 MWT (chosen velocity) (m/s)**: EG: pre = 0.87 ± 0.15 and post =0.85 ± 0.12 ; CG: pre: 0.84 ± 0.12 and post: 0.98 ± 0.13 **10 MWT (fast velocity) (m/s):** EG: pre = 1.20 ± 0.13 and post = 1.53 ± 0.21; CG: pre = 1.37 ± 0.14 and post: 1.24 ± 0.23 $^*p < .05$	**ΔUPDRS Motor (points)** EG:↓0.54 (unachieved) CG: ↓0.35 (unachieved) **Δ 10 MWT chosen velocity (m/s):** EG: ↓0.2 (unachieved) CG: ↓0.14 (unachieved) **Δ10 MWT fast velocity(m/s):** EG: ↓0.33 (achieved) CG :↓0.13 (unachieved)

Symbology: Δ = variation; ↑ increase or improve and ↓ decrease or reduction. Abbreviation: ABC = Activities-specific Balance Confidence questionnaire ; FGA = Functional Gait Assessment; FOG-Q = Freezing of Gait Questionnaire; EG = Experimental group; CG = Control group and ACG = Active control group; PDQ-39 = Parkinson's Disease Questionnaire; MDC = Minimal Detectable Change; MMSE = Mini-Mental State Examination; 6MWT = 6 minutes walking test; TUG = Timed up and go; UPDRS = Unified Parkinson's Disease Rating; 10MWT = 10 metres walking test.

Table 4. Characteristics of the interventions and effect on gait and ambulation parameters reported in the investigations (*continued*).

Authors/ Quality	Characteristics of the intervention		Outcomes	Results of the intervention		
	Modality	**Duration**		**UPDRS (points)**	**Balance and walking**	**MCD Results**
Shen et al. (2014) PEDro: 10/10	EG: Balance and walking training ACG: Strength training of lower limbs	12 weeks, 3 supervised sessions and 5 sessions per week of home-based training	ABC, sit-to-stand of chair and walking characteristics (velocity and steps)	Does not applied post training	**ABC (%)** EG : pre = 75.8 ± 15.1 and post = 80.1 ± 16.5; CG: pre = 70.6 ± 18.3 and post = 73.7 ± 17.9 **10 MWT(cm/s)*:*** EG : pre = 96.5 ± 15.2 and post = 103.6 ± 13.2* ; CG: pre = 97.8 ± 13.6 and post = 106.8 ± 11.1* **Length of steps (cm)** : EG : pre = 109.9 ± 17.9 y post = 124.6 ± 16.5*; CG: pre = 115.7 ± 13.0 and post = 118.8 ± 12.1 **p* < .05	**Δ ABC (%)** EG = ↑6.3 (unachieved) CG = ↑2.8 (unachieved) **Δ 10 MWT (m/s)** EG = ↑0.96 (achieved) CG = ↑1.02 (achieved)
Shen et al. (2015) PEDro: 10/10			Number of falls in 12 months. Rate of falls per years and spatio-temporal characteristic of walk		**Number of falls:** EG: pre = 2:20 and post = 6:16 ; ACG: pre = 11:12 and post = 13:10 **Rate of falls:** EG : pre = 0.57 and post = 0.29; ACG: pre = 0.76 y post 1.52 **Latency in postural control:** EG : pre = 130.0 ± 12.0 and post = 8.4±15.8 ; ACG: pre = 132.2 ± 10.3 and post = 3.7 ± 11.6 **Walking velocity:** EG : pre = 96.5 ± 15.2 and post = 10.4±13.9; ACG : pre = 97.8 ± 13.6 and post = 6.7 ± 15.6 **Length of steps:** EG : pre = 109.9 ± 17.9 and post = 13.3 ± 14.8 ACG: pre = 115.7 ± 13.0 and post = 2.6 ± 12.5	**Δ 10 MWT (m/s)** EG = ↑0.86 (achieved) CG = ↑0.91 (achieved)
Shulman et al. (2012) PEDro: 8/10	High-intensity aerobic exercises (HAE) and Low-intensity aerobic exercises (LAE) on treadmill and Resistance exercises and stretches (RE)	36 sessions, 3 times per week for 3 months	UPDRS, MMSE, S&E disability scale	Does not applied post training	**TM6m** HAE: pre = 1374.2 ± 57.4 and post = 1451.2 ± 62.5 LAE: pre = 1446.7 ± 95.2 and post = 1607.7 ± 111.6* RE: pre = 1395.5 ± 75.6 and post = 1502.4 ± 81.6* **p* < .05	**Δ6 MWT** (m) HAE = ↑77 (unachieved) LAE = ↑161 (achieved) RE = ↑107 (achieved)
Steffen et al. (2012)	Walking forward and backward. Resistance training	10 months, 2 times per week, 60 minutes	UPDRS, 6MWT, Berg Scale and TUG	**Mental:** pre = 3.2 ± 2.4 and post = 1.6 ± 1.7 **DLA** pre = 14 ± 7 and post = 12 ± 6 **Motor:** pre = 13 ± 5 and post = 12 ± 3 **Total:** pre = 30 ± 13 y post = 26 ± 9	**6 MWT (m)** Pre = 309 ± 123 and post = 370 ± 114 **Berg Scale (points)** Pre = 48 ± 6 and post = 49 ± 6 **TUG (s)** Pre = 16 ± 8 and post = 14±4	**ΔUPDRS (points)** Mental = ↓1.2 (unachieved) DLA = ↓0.8 s (unachieved) Motor = ↓0.14 (unachieved) Total = ↓0.06 (unachieved) Δ6 MWT (m) ↑61 m (unachieved)
Wroblewska et al. (2019)	Nordic walk	12 weeks, 2 times per week	FOG-Q, TUG, provocation test for freezing and movement blocks	Does not applied post training	**FOG-Q (points) :** EG: pre = 12.6 ± 1.4 and post = 7.1 ± 1.7 ; GC: pre = 7.1 ± 1.7 and post = 7.1 ± 1.7 **TUG (s) :** EG: pre = 17.2 ± 1.4 and post = 12.6 ± 1.4; GC: pre = 12.6 ± 1.4 and post = 12.6 ± 1.4	**ΔTUG (s)** EG ↓4.6 s (unachieved) CG = 0 s (unachieved)

Symbology: Δ = variation; ↑ increase or improve and ↓ decrease or reduction. Abbreviation: ABC = Activities-specific Balance Confidence questionnaire ; FGA = Functional Gait Assessment; FOG-Q = Freezing of Gait Questionnaire; EG = Experimental group; CG = Control group and ACG = Active control group; PDQ-39 = Parkinson's Disease Questionnaire; MDC = Minimal Detectable Change; MMSE =Mini-Mental State Examination; 6MWT = 6 minutes walking test; TUG =Timed up and go; UPDRS =; Unified Parkinson's Disease Rating; 10MWT =10 metres walking test.

Only one study reported a positive statistically significant change in the 10MWT (Shen et al., 2014). However, two other studies achieved a clinically positive MDC in the evaluation of 10MWT after the strength training (Santos et al. 2017 y Shen et al. 2015). In addition, one study reported a statistically significant and clinically significant change in the 6MWT in intervened groups with low-intensity aerobic exercise and muscle resistance. In contrast, the high-intensity group of the same research only reported a clinical effect (Shulman et al., 2012). Dibble et al. (2015) inform a statistically positive change in groups training in eccentric and groups training in concentric modality of exercise.

Quality of the evidence

The PEDro scale was applied to 7 of the 9 studies included in this systematic review. Wroblewska et al. (2019) and Steffen et al. (2012) were excluded from the PEDro evaluation because they were pilot studies. The details are in Table 4.

DISCUSSION

This systematic review focused on analysis of the effect of long-term physical therapy and exercise in older people living with PD. Aerobic exercise, endurance exercises, strength training and balance exercises obtained better outcomes. The protocols follow a progression from low to high intensity.

Shein et al. (2015) obtained better MDC walking velocity results in both intervened groups. The balance training group obtained ↑0.86, and the strength training group obtained ↑0.91. Shulman et al. (2012) showed significant changes in 3 intervened groups: High-intensity = ↑77, Low-intensity = ↑161, and stretching and strengthening exercises = ↑107. Santos et al., (2017) report an MDC in the walking velocity of both groups of ↓0.33. The above mentioned articles' all share strength and muscular endurance components in their protocols, all of which progressed from low to high intensity. However, the three articles have differences in the duration of the intervention. Santos et al. (2017) executed 8 weeks of supervised training, followed by 4 weeks of unsupervised training (12 weeks). In contrast, Shen et al. (2015) and Shulman et al. (2013) followed an exclusive supervised program of 12 weeks. Even with the difference in the protocols, all three articles include training based on walking on treadmills or walking or running frontwards and backwards, with strength training focused on lower limbs, using the exercises of flexo-extension of knees and hips.

People living with PD experience changes in their walking characteristics, like an increase in the number of steps, a decrease in the length of steps, more time spent in the stance phase of walking in normal gait or during freezing of gait, asymmetric movement in lower and upper limbs, trunk rigidity and decrease in the range of movement of hips, knees and ankles (Zanardi et al., 2021). All the changes in walking that people with PD experience led to a decrease in walking velocity. Zanardi et al. (2021) shows no improvement in the walking velocity of people with PD; this could be due to comparisons being drawn between PD population and a healthy control group. In contrast, Radder et al. (2020) include 191 clinical trials with an objective to compare conventional physical therapy against new modalities of exercise: Conventional physical therapy, endurance training, treadmill training, strategy training, dance, martial arts, aerobic exercises, hydrotherapy, balance and walking training, double task training, exergaming and Nordic walk. Although, Radder et al. (2021) showed an increase in walking and balance parameters, this review did not discriminate based on age or stage of PD, instead comparing people with PD with themselves, possibly leading to improved results.

The principal limitation of our systematic review is the lesser number of studies that report the effect of long-term exercise interventions in people with PD. Also, the wide variety of scales used to evaluate change in each study negatively impacted this review. This factor makes it difficult to compare the various studies. Despite these limitations, the quality of the study was high and contributed to enriching this review.

CONCLUSIONS

Based on the results of the present systematic review, it can be concluded that a 12 weeklong intervention (long-term) is superior in improving the walking and balance parameters of people with PD. Specifically, interventions with modalities of high-intensity strength training, progressive endurance training, aerobic exercise and balance and walking exercise most improved the clinical outcomes in people with PD. The common factor in all the studies was the frequency of two times per week, and progressive load, trying to reach maximal repetitions, series and load.

From the literature on exercise and PD, it can be concluded that short-term interventions of 6 weeks of training predominate the field. Therefore, to improve the quality of new studies related to health and sport, it is suggested that new clinical trials related to the field of health and exercise choose interventions of more than 12 weeks in an attempt to produce more literature related to long-term training in people over 60 years old. Additionally, further research could include supervised interventions, starting from the earliest stages of PD (I and II), and include modalities of strength, resistance and balance training with a frequency of a minimum of two times per week. All these recommendations are necessary to secure clinically and statistically significant change. Implementing new research combining conventional exercise with Tai Chi, Ai Chi, music-therapy, and dance is essential for long-term rehabilitation research.

AUTHOR CONTRIBUTIONS

The idea for the article was conceived by Nicole Fritz. The literature search and data extraction was performed by Jaime Silva, Nicolas Velásquez, Matías Rosas Ruiz and Sandra Vargas. The data analysis was carried out by Jaime Silva, Nicolas Velásquez, Matías Rosas Ruiz and Sandra Vargas and Nicole Fritz. Nicole Fritz and Cristian Mansilla critically revised the work. All authors read and approved the final manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

REVIEW ARTICLE

Assessing athlete readiness using physical, physiological, and perceptual markers: A systematic review and meta-analysis

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ABSTRACT

This systematic review and meta-analysis evaluated the validity of tests / markers of athletic readiness to predict physical performance in elite team and individual sport athletes. Ovid MEDLINE, Embase, Emcare, Scopus and SPORT Discus databases were searched from inception until 15 March 2023. Included articles examined physiological and psychological tests / markers of athletic readiness prior to a physical performance measure. 165 studies were included in the systematic review and 27 studies included in the meta-analysis. 20 markers / tests of athletic readiness were identified, of which five were meta-analysed. Countermovement jump (CMJ) jump height had a large correlation with improved 10m sprint speed / time (r = 0.69; *p* = .00), but not maximal velocity (r = 0.46; *p* = .57). Non-significant correlations were observed for peak power (r = 0.13; *p* = .87) and jump height (r = 0.70; *p* = .17) from squat jump, and 10m sprint speed / time. CMJ jump height (r = 0.38; *p* = .41) and salivary cortisol (r = -0.01; *p* = .99) did not correlate with total distance. Sub-maximal exercise heart rate (r = -0.65; *p* = .47) and heart rate variability (r = 0.66; *p* = .31) did not correlate with Yo-Yo Intermittent Recovery Test 1 performance. No correlation was observed between blood C-reactive protein and competition load (r = 0.33; *p* = .89). CMJ jump height can predict sprint and acceleration qualities in elite athletes. The validity of the other readiness tests / markers meta-analysed warrants further investigation.
Keywords: Elite athletes, Athlete readiness, Physical performance, Athlete monitoring.

Cite this article as:
Janetzki, S. J., Bourdon, P. C., Burgess, D. J., Barratt, G. K., & Bellenger, C. R. (2023). Assessing athlete readiness using physical, physiological, and perceptual markers: A systematic review and meta-analysis. *Scientific Journal of Sport and Performance*, *2*(3), 339-380. https://doi.org/10.55860/AGRH6754

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Submitted for publication May 12, 2023.
Accepted for publication June 05, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/AGRH6754

INTRODUCTION

The demands and nature of modern day professional sport has caused an increase in not only the physiological demands on athletes but psychological stress from commercial obligations, sponsors, media, education and family (Ryan et al., 2020). Therefore, it is of critical importance performance coaches have a comprehensive understanding of the competing demands on their athletes, their fatigue and recovery status, and ultimately their "*readiness*" to perform in training and competition (Ryan et al., 2020). Athlete monitoring is now standard practice in professional sport (Taylor et al., 2012), with the information collected used to inform performance staff of an athlete's injury risk and readiness to perform (Taylor et al., 2012; Thorpe et al., 2017). The primary goal of athlete monitoring systems is to monitor training load and the athletes' responses to training and competition stress to inform decision making on recovery and availability for subsequent training and competition (Bourdon et al., 2017). Importantly, an intricate understanding of the stress on athletes is fundamental to the subtle manipulation of training load to maximise favourable and functional adaptations to maximise performance (Impellizzeri et al., 2019).

Often the difficulties with monitoring team sport athletes in particular, is the individual variability between athletes in their response to modifiable (health, sleep and training status) and non-modifiable (genetics, weather, and pressure and expectation from media and supporters) factors (Impellizzeri et al., 2019). Indeed, the prescription of the identical training load for one athlete may evoke a completely different internal, psychophysiological response in other athletes from the same team (Bouchard et al., 2011; Mann et al., 2014; Smith, 2003).

With improvements in technologies used to monitor athletes, the current practice in professional sport is to assess athlete readiness for training and competition, and tolerance to training load, at the individual level. Typically, this is comprised of neuromuscular assessments including countermovement jump (CMJ) and squat jump (SJ) (Cormack et al., 2013), fitness tests (i.e., Yo-Yo Intermittent Recovery Test 1 (Yo-Yo IR1)) (Veugelers et al., 2016), and autonomic nervous system assessment using heart rate parameters (i.e., heart rate variability (HRV) and heart rate recovery (HRR) (Plews, Laursen, Stanley, et al., 2013). More invasive measures such as testing biological markers are also commonly used, with inflammatory markers such as creatine kinase (CK) suggested to be a valid and reliable indicator of fatigue in team sport athletes (Hecksteden et al., 2016; Nédélec et al., 2012). Furthermore, whilst the importance of physiological recovery is fundamental to athlete readiness for training and competition, there is well-established literature supporting the use of psychological markers of training status to monitor individual athlete response (Borresen & Lambert, 2009; Raglin, 2001). These psychological recovery markers, commonly assessed through a range of psychological wellness questionnaires (Saw et al., 2015), provide an athlete's individual perception of readiness and comprise a critical component of the recovery-fatigue monitoring process (Kellmann et al., 2018; Saw et al., 2016).

Previous studies that have established changes in readiness tests and markers, particularly HRV, suggest a stronger correlation with measures of performance as opposed to other isolated measures (Bellenger et al., 2016; Plews, Laursen, Kilding, et al., 2013). Importantly, a distinguishing feature of the current review was the investigation of tests and markers of readiness in the context of gold standard measures of athletic performance using correlation analysis. Furthermore, despite the volume of studies which, in isolation, have investigated the use of various tests and markers of athletic readiness as an indicative measure of performance, no study has conducted a holistic investigation and analysis of the various readiness tests and markers used to assess fitness and fatigue in elite team and individual sport athletes.

Given the rise in the reliance and application of these markers and tests for practitioners in sport and exercise science, the aim of this review was to identify the most valid tests and measures of athletic readiness to predict physical performance in elite athletes.

MATERIAL AND METHODS

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for improved reporting of systematic reviews (Moher et al., 2009).

Literature search

A systematic search of the literature was conducted on 3 November 2021 in the following databases: Ovid MEDLINE, Embase, Emcare, SPORT Discus and Scopus. Database update alerts were monitored until 15 March 2023 for any additional studies that met the inclusion criteria. Database searches were complemented with pearling of reference lists for relevant studies which satisfied the inclusion criteria.

Title, abstract and keyword searches were conducted in the aforementioned databases using the following search strategy (see Supplementary Table 1 for the master search strategy) developed in MEDLINE and Emcare, which was revised and amended for the remaining databases:

1. Elite athletes

AND

2. Tests and / or markers of athletic readiness

AND

3. Physical measures of athletic performance

Eligibility criteria

To be eligible for inclusion in this review, study participants must have been elite, professional able-bodied athletes of any gender competing in team or individual sports. Study participants were considered to have met the inclusion criteria if they satisfied tiers four and five of the classification frameworks developed by McKay et al. (McKay et al., 2022), with the exception of NCAA and elite junior or underage athletes who were excluded as they were not considered professional for the purpose of this review. Studies needed to assess more than one participant using a relevant test and marker of athletic readiness, prior to a subsequent measure of athletic performance. Only studies which analysed participants using a test and marker of readiness in a rested or sub-maximal state were included, due to the disruption of physiological homeostasis following near, or maximal physical exertion (Bellenger et al., 2016). Studies which investigated markers and tests of readiness in the context of other interventions which disrupted a homeostatic state (i.e., caffeine ingestion or heat exposure) were eligible for inclusion provided a placebo / control group's data could be extracted independently of the intervention group, and there was no cross-over of participants to control and / or intervention groups during the study. Studies' intervention period could not exceed 12 months or one season. Studies measuring HRR were only included if heart rate was measured following sub-maximal exercise, in line with previously established sub-maximal heart rate assessment protocols (Buchheit et al., 2009). Studies using session rating of perceived exertion (sRPE) as a performance measure were only included if the subjective measure of load was calculated from a competition or match setting. Studies which analysed sport-specific readiness and performance (i.e., 7-stroke max and repeated sprint ability) tests were not eligible for inclusion as their application was not generalisable, as were unpublished, non-English, or qualitative studies.

Studies were eligible for inclusion in the meta-analysis if the relationship between the marker and test of performance readiness and the subsequent performance measure were analysed using Pearson product-moment correlation coefficient or Spearman's rank correlation coefficient. To improve the generalisability of the findings, studies were only meta-analysed if three or more studies analysed an identical, standardised readiness test and marker in the context of an analogous performance outcome. Where necessary, the direction of relationships was transformed to a positive value to indicate an improvement or decrement in performance. For example, the time to complete a time trial and the average speed in a time trial provide different directions. Therefore, studies included in the meta-analysis were amended to ensure consistency in the direction of the reported relationship between analogous readiness markers and tests, study designs, and performance outcomes.

Studies analysing sub-maximal exercise heart rate were eligible for inclusion if exercise heart rate was measured following a period of at least three minutes of sub-maximal exercise intensity, so a steady state heart rate was established (Buchheit, 2014; Cerretelli & Di Prampero, 1971). For HRV, meta-analyses were only conducted on studies which reported indices of standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots (SD1), root-mean-square difference of successive normal R–R intervals from time-domain analysis (RMSSD) and high frequency power (HFP) as measures of pure parasympathetic modulation based on the findings and recommendations of Bellenger et al. (Bellenger et al., 2016).

Study selection

Studies identified in the systematic search were exported into a reference management software program (Endnote version X8.2, Thomson Reuters, 2012). All articles were subsequently imported into Covidence (Covidence Systematic Review Software, Veritas Health Innovation, 2013) where all duplicates were removed. Studies were initially assessed for eligibility by title and abstract screening against the eligibility criteria in Covidence, where irrelevant studies were excluded. The remaining studies were assessed for full-text eligibility using the eligibility criteria. Screening was conducted independently by two investigations (SJJ and GKB), with conflicts resolved by consensus.

Data extraction was conducted by the lead author (SJJ) and confirmed by a second investigator (GKB). The following information was obtained from the included studies: publication details (year, author(s), country), participant characteristics, study design (longitudinal (pre-post test(s) and marker(s) of readiness) or cross-sectional), results (athletic readiness test(s) / marker(s), performance measure(s)), duration of time between the fatiguing exposure and test of readiness and performance, and the relationship between the readiness test and performance measure (acute (<48 hours) or chronic (>48 hours)), based on the passage of time between the assessment of the readiness test and / or marker and the subsequent performance measure.

Risk of bias assessment

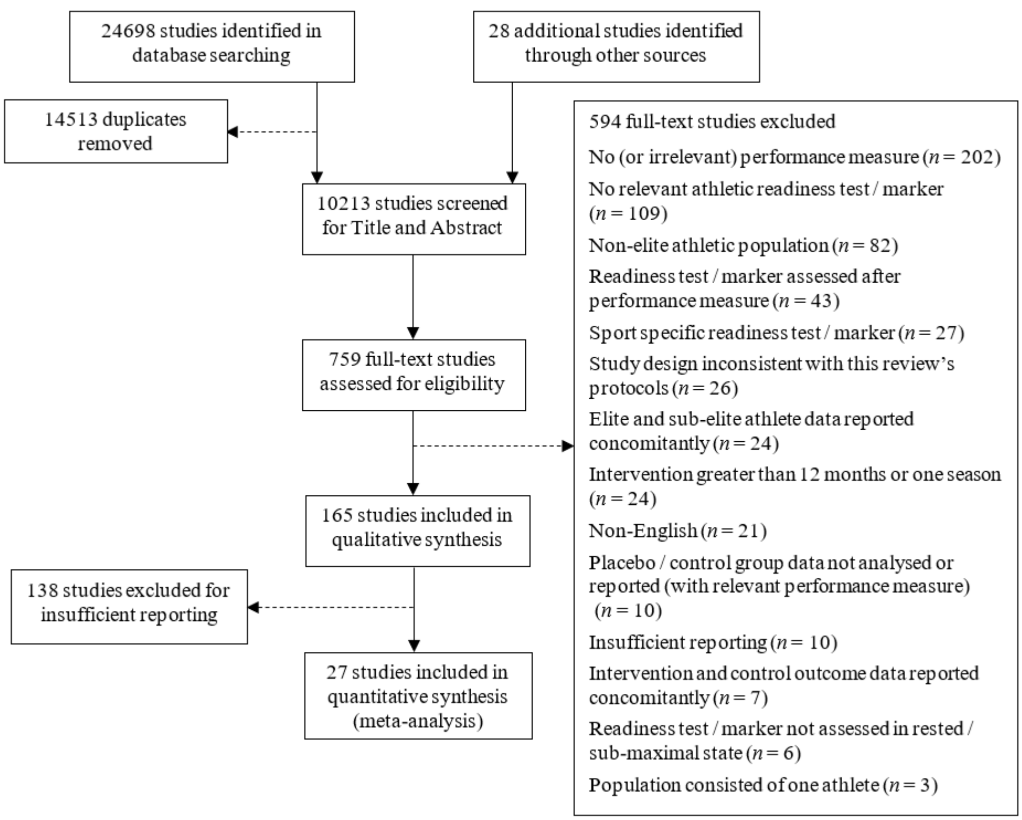
The Cochrane Collaboration tool was used by the lead author (SJJ) and confirmed by a second investigator (GKB) to assess risk of bias (Higgins et al., 2011). The tool was used to assess selection, performance, detection, attrition and reporting bias from the studies identified from the systematic search.

Statistical analysis

Random effects meta-analyses were performed in Stata 16.1 (College Station, Texas) to assess the relationship between homogenous markers and tests of performance readiness, and performance measures. All correlation coefficient data from the included studies were normally distributed using the Fisher Z-Transformation to calculate the standard error, before being transferred back into Pearson product-moment correlation coefficients for reporting and presentation. Data were presented as Pearson product-moment correlation coefficient (r) ± 95% confidence interval (CI) with statistical significance set at $p < .05$. Qualitative interpretations of the correlation coefficients were applied based on the following framework: 0.00-0.09, trivial; 0.10-0.29, small; 0.30-0.49, moderate; 0.50-0.69, large; 0.70-0.89, very large; 0.90-1.00, nearly perfect (Hopkins, 2000). The presence of statistical heterogeneity was determined by the I^2 statistic and interpreted using the framework developed by Higgins et al. (Higgins et al., 2019).

Meta-analyses were conducted on indices of the following markers and tests of performance readiness: CMJ, biomarkers, SJ, sub-maximal exercise heart rate, and HRV which were sub-grouped into acute (<48 hours) and chronic (>48 hours). These markers were further grouped into cross-sectional and / or longitudinal study designs for analysis, as well as whether the performance measure(s) assessed the marker and test of readiness in a training or competition setting. Identical markers and tests of readiness were eligible to be analysed with different performance measures provided the performance measures assessed different psychophysiological qualities. To ensure uniformity in the analyses and reporting, and where appropriate to do so, data were presented with a positive correlation.

RESULTS



Note. n number of studies.

Figure 1. Literature search flow chart.

The initial search identified 24698 studies, with 28 studies identified through other sources. Once 14513 studies were removed as duplicates, a further 9454 studies were identified as irrelevant by title and abstract screening. 759 studies were reviewed by full text for inclusion. A summary of the search, including the number of studies included in the qualitative synthesis and meta-analysis, is shown in Figure 1. A summary of the 165 studies included in the qualitative synthesis is provided in Table 1.

Table 1. Summary of studies included in the qualitative synthesis.

Study	***n***	**Athletes**	**Study design**	**Readiness marker(s) / test(s)**	**Performance measure context**	**Relationship**
Costa et al., 2022	M: 11	Beach Soccer	Longitudinal	Wellness Questionnaire (HI)	Training	Acute
Gaviglio & Cook, 2014	M: 22	Rugby Union	Longitudinal	Biomarker (salivary T, T:C)	Competition	Acute
Loturco et al., 2018	M: 9 F: 7	Athletics	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Training	Acute
Balthazar et al., 2012	M: 8	Triathlon	Cross-sectional	Biomarker (salivary T, C)	Competition	Acute
Morris et al., 2022	M: 14	ARF	Cross-sectional	CMJ (PCF, PEF, eccentric time, concentric time, FT, eccentric: concentric time, PEP, PCP, peak eccentric velocity, peak concentric velocity, jump height, peak eccentric RFD, peak concentric RFD)	Training	Acute
McLellan et al., 2010	M: 17	Rugby League	Longitudinal	Biomarker (blood CK, and salivary T, C)	Competition	Chronic
Crewther et al., 2012	M: 64	Rugby Union	Cross-sectional	Biomarker (salivary T)	Training	Acute
Gaviglio et al., 2014	M: 22	Rugby Union	Longitudinal	Biomarker (salivary T, C, T:C)	Competition	Acute
Loturco et al., 2014	M: 9 F: 10	Karate	Cross-sectional	CMJ (jump height) Squat Jump (jump height, relative mean propulsive power)	Training	Acute
Webster et al., 2022	M: 15	Cricket	Cross-sectional	CMJ (jump height)	Competition	Chronic
Henderson et al., 2019	M: 20	Rugby Sevens	Longitudinal	Wellness Questionnaire (soreness, sleep, stress, fatigue, recovery) Groin Squeeze Assessment (0^0)	Competition	Chronic
Le Panse et al., 2010	M: 13 F:13	Powerlifting	Cross-sectional	Biomarker (salivary T, C, DHEA)	Competition	Acute
Loturco, Pereira, et al., 2015	M: 14	Athletics	Cross-sectional	CMJ (jump height) Squat Jump (jump height) Horizontal Jump	Competition	Chronic
Knöpfli et al., 2001	M: 4 F: 5	Cross-country skiing	Longitudinal	Biomarker (dopamine, epinephrine, norepinephrine)	Competition	Acute
Krustrup et al., 2003	M: 17	Soccer	Longitudinal	Biomarker (blood lactate, plasma K+)	Training	Acute
Staunton et al., 2017	F: 12	Basketball	Longitudinal	Sleep (time, efficiency)	Competition	Acute

Hansen et al., 2019	M: 12	Gymnastics	Cross-sectional	CMJ (jump height, peak power) Drop Jump (jump height)	Competition	Acute
McMahon et al., 2021	M: 15	Hockey	Longitudinal	Biomarker (CK) Wellness Questionnaire (soreness)	Competition	Chronic
Loturco, D'Angelo, et al., 2015	M: 13 F: 9	Athletics	Cross-sectional	CMJ (jump height, peak force) Squat Jump (jump height, peak force) Horizontal Jump (distance (m))	Training	Acute
Pojskic et al., 2018	M: 38	Basketball	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Training	Chronic
Secomb, Farley, et al., 2015	M: 18	Surfing	Cross-sectional	CMJ (peak force, peak velocity, jump height, stiffness) Squat Jump (peak force, peak velocity, jump height) IMTP (peak force, relative force)	Training and Competition	Acute
Nakamura et al., 2020	M: 11	Futsal	Longitudinal	HRV (RMSSD)	Training	Acute
Hooper et al., 1993	M: 5 F: 8	Swimming	Longitudinal	Biomarker (blood cortisol, epinephrine, norepinephrine)	Training	Acute
Thorpe et al., 2015	M: 10	Soccer	Longitudinal	Wellness Questionnaire (fatigue, sleep, soreness) CMJ (jump height) HRV (lnRMSSD) HRR	Training	Acute
Turner et al., 2015	M: 17	Rugby Union	Cross-sectional	CMJ (jump height)	Training	Chronic
Rabbani et al., 2018	M: 14	Soccer	Longitudinal	Sub-maximal exercise HR HRR	Training	Chronic
Colyer et al., 2017	M: 8 F: 5	Skeleton	Longitudinal	CMJ (max centre of mass displacement, peak power, mean power, RFD)	Training	Acute
Lombard et al., 2021	M: 23	Hockey	Longitudinal	CMJ (jump height)	Competition	Chronic
Peñailillo et al., 2015	M: 9	Soccer	Longitudinal	Biomarker (salivary T, C, IgA)	Competition	Acute
Selmi, Levitt, et al., 2022	M: 16	Soccer	Longitudinal	Wellness Questionnaire (physical freshness)	Training	Acute
Hills & Rogerson, 2018	M: 37	Rugby Union	Longitudinal	Wellness Questionnaire	Training	Acute
Loures et al., 2014	M: 21 F: 7	Kayaking (K1)	Longitudinal	Biomarker (blood lactate)	Competition	Acute
Balsalobre-Fernández et al., 2014	M: 12 F: 3	Athletics	Longitudinal	CMJ (jump height) Biomarker (salivary C)	Training	Acute
Spiteri et al., 2014	F: 12	Basketball	Cross-sectional	CMJ (jump height) IMTP (peak force)	Training	Acute
Stojanovic et al., 2012	M: 24	Basketball	Cross-sectional	CMJ (jump height)	Training	Acute

Maior et al., 2018	M: 20	Soccer	Longitudinal	Biomarker (blood CK)	Competition	Acute
Saidi et al., 2022	M: 14	Soccer	Longitudinal	Biomarker (blood CRP, CK, creatinine) CMJ (jump height) Squat Jump (jump height) Wellness Questionnaire (HI)	Training and Competition	Acute and Chronic
Shearer et al., 2015	M: 12	Rugby Union	Cross-sectional	Wellness Questionnaire (BAM)	Training	Acute
Malone et al., 2017	M: 22	Gaelic Football	Longitudinal	HRV (lnSD1) HRR Sub-maximal exercise HR	Training	Acute
Gastin et al., 2013	M: 27	ARF	Longitudinal	Wellness Questionnaire (general muscle strain, hamstring strain, quadriceps strain, stress)	Competition	Acute
R. Gathercole et al., 2015	F: 12	Rugby Sevens	Longitudinal	CMJ (RFD, time to peak power, time to peak force, velocity at peak power, peak displacement, flight time, FT:CT) Wellness Questionnaire (HI)	Training	Acute
Requena et al., 2014	M: 25	Soccer	Longitudinal	CMJ (flight time, velocity at take-off) Drop Jump (flight time, contact time, velocity at take-off)	Training	Acute
Silva et al., 2014	M: 14	Soccer	Longitudinal	CMJ (jump height) Biomarker (blood C, T:C, antioxidant, gluthione peroxidase, superoxide dismutase gluthione peroxidase ratio)	Competition	Chronic
Guilhem et al., 2015	M: 9 F: 15	Athletics	Longitudinal	Wellness Questionnaire (POMS) Biomarker (salivary T, C, AA, IgA, chromogranin A, and blood CK)	Training	Chronic
Díaz Gómez et al., 2013	M: 8 F: 3	Swimming	Longitudinal	Biomarker (salivary AA, chromogranin, nitrate, and blood adrenaline, noradrenaline, dopamine)	Training	Chronic
Hulin et al., 2019	M: 32	Rugby League	Longitudinal	Sub-maximal exercise HR	Training	Acute
Calleja-Gonzalez & Terrados, 2014	M: 8	Basketball	Longitudinal	Biomarker (blood T, C, T:C, CK)	Competition	Chronic
Clarke et al., 2015	F: 12	Rugby Sevens	Longitudinal	Biomarker (blood CK)	Competition	Acute
Moncef et al., 2012	M: 40	Handball	Cross-sectional	CMJ (jump height) Squat Jump (jump height) Vertical Jump (jump height)	Training	Chronic

Silva & Paiva, 2016	F: 67	Rhythmic Gymnastics	Longitudinal	Sleep (duration) Wellness Questionnaire (SCAT-A, PSQI, ESS)	Competition	Not reported
Bonifazi et al., 2000	M: 8	Swimming	Longitudinal	Biomarker (blood C)	Competition	Chronic
Doeven et al., 2019	F: 12	Rugby Sevens	Cross-sectional	Wellness Questionnaire (fatigue, soreness)	Competition	Acute
Bok & Jukić, 2019	M: 11	Soccer	Longitudinal	Biomarker (blood CK)	Competition	Acute
Emmonds et al., 2019	F: 10	Soccer	Cross-sectional	CMJ (jump height, RFD) Squat Jump (jump height, RFD) Drop Jump (jump height)	Training	Acute
Atlaoui et al., 2006	M: 9 F: 5	Swimming	Longitudinal	Biomarker (urinary adrenaline, adrenaline:noradrenaline ratio)	Competition	Chronic
Chamari et al., 2003	M: 9 F: 1	Windsurfing	Longitudinal	Heart rate reserve	Competition	Acute
Hunkin et al., 2014	M: 29	ARF	Longitudinal	Biomarker (blood CK)	Competition	Acute
Selmi et al., 2021	M: 20	Soccer	Longitudinal	Wellness Questionnaire (HI)	Training	Acute
Enes et al., 2021	M: 23	Soccer	Cross-sectional	CMJ (jump height) Sit and Reach Test	Training	Chronic
Mielgo-Ayuso et al., 2017	F: 40	Volleyball	Cross-sectional	Biomarker (blood T, ACTH, C, free T, T:C, free T:C) Wellness Questionnaire (SCAT, STAI, CSAI 2-7, OSQ, GHQ, Psychological Characteristics Related to Sport Performance Questionnaire)	Training	Acute
Messias et al., 2018	M: 10	Kayaking (K1, C1, C2)	Cross-sectional	Wellness Questionnaire (POMS, SCAT, PSQI, ESS)	Training	Acute
Mäestu et al. 2005	M: 11	Rowing	Longitudinal	Biomarker (blood T, C)	Training	Chronic
Haller et al., 2019	M: 26	Soccer	Longitudinal	Biomarker (blood cell-free DNA) Wellness Questionnaire (VAS)	Training and Competition	Acute
Cullen et al., 2021	M: 37	Gaelic Football	Longitudinal	Wellness Questionnaire (mood, sleep (quality and duration), energy, soreness, nutrition, stress, health)	Training and Competition	Acute
Saidi et al., 2019	M: 18	Soccer	Longitudinal	Squat Jump (jump height)	Training	Chronic
Lum & Joseph, 2020	M: 18 F: 6	Floorball	Longitudinal	CMJ (jump height)	Training	Acute
Nunes et al., 2011	F: 12	Basketball	Longitudinal	Biomarker (salivary T)	Training	Chronic
McEwan et al., 2020	M: 12	Cricket	Longitudinal	Wellness Questionnaire (Core-CSD)	Competition	Acute

Solana-Tramunt et al., 2019	F: 12	Synchronised Swimming	Longitudinal	HRV (lnRMSSD)	Training	Acute
Purge et al., 2006	M: 11	Rowing	Longitudinal	Biomarker (blood T, C)	Training	Chronic
Costa et al., 2019	F: 20	Soccer	Longitudinal	HRV (lnRMSSD) Sleep (time, efficiency)	Training and Competition	Acute
Tiernan et al., 2020	M: 19	Rugby Union	Longitudinal	Biomarker (salivary C)	Training	Chronic
Rodríguez-Fernández et al., 2021	M: 14	Basketball	Cross-sectional	CMJ (jump height)	Training	Chronic
Hauer et al., 2020	M: 12	Lacrosse	Longitudinal	Wellness Questionnaire (TQR, SRSS) HRV (RMSSD)	Competition	Acute
Costa et al., 2021	F: 34	Soccer	Longitudinal	HRV (lnRMSSD, lnHFP) Sleep (duration, efficiency)	Training and Competition	Acute
Iizuka et al., 2020	M: 4 F: 4	Badminton	Longitudinal	HRV (RMSSD, HFP)	Training	Acute
Bouaziz et al., 2016	M: 16	Rugby Sevens	Longitudinal	Biomarker (urinary C, cortisone, cortisol: cortisone ratio, adrenaline, adrenaline:noradrenaline ratio)	Training	Chronic
Cormack et al., 2008	M: 22	ARF	Longitudinal	CMJ (FT:CT) Biomarker (salivary T, C, T:C)	Competition	Acute and Chronic
Crewther et al., 2009	M: 24	Rugby Union	Cross-sectional	Biomarker (salivary T, C, T:C)	Training	Acute
Russell et al., 2021	F: 9	Netball	Longitudinal	Biomarker (salivary C, AA) Wellness Questionnaire (SRSS)	Competition	Acute and Chronic
Morales et al., 2019	F: 10	Soccer	Longitudinal	Wellness Questionnaire (RESTQ-Sport) HRV (RMSSD, HFP)	Training	Acute and Chronic
Crewther et al., 2020	M: 29	Rugby Union	Longitudinal	Biomarker (salivary C) Wellness Questionnaire	Competition	Acute
Moalla et al., 2016	M: 14	Soccer	Longitudinal	Wellness Questionnaire (HI)	Training and Competition	Acute
Watanabe et al., 2019	F: 57	Baseball	Cross-sectional	CMJ (jump height) Vertical Jump (jump height)	Competition	Chronic
Coppalle et al., 2019	M: 26	Soccer	Longitudinal	Biomarker (blood LDH, CK, CRP)	Competition and Training	Chronic
Bosco et al., 1996	M: 32	Soccer	Cross-sectional	CMJ (jump height) Biomarker (blood T, C)	Training	Acute
Ingebrigtsen et al., 2014	M: 34	Soccer	Cross-sectional	Sub-maximal exercise HR	Training	Acute
West et al., 2011)	M: 39	Rugby League	Cross-sectional	CMJ (jump height) IMTP (peak force, RFD, force 110 ms)	Training	Acute
Secomb, Lundgren, et al., 2015)	M: 15	Surfing	Cross-sectional	CMJ (jump height, peak force) Squat Jump (jump height, peak force) IMTP (peak force)	Training	Acute

Boraczyński et al., 2020	M: 25	Soccer	Cross-sectional	CMJ (jump height, peak power)	Training	Acute and Chronic
Cunningham et al., 2018	M: 15	Rugby Union	Cross-sectional	CMJ (jump height, peak power) IMTP (peak force, force at 250 ms) Drop Jump (jump height, RSI)	Competition	Chronic
Cook & Beaven, 2013	F: 12	Netball	Longitudinal	Biomarker (salivary T)	Training	Acute
Bishop et al., 2003	F: 14	Hockey	Longitudinal	Biomarker (blood lactate, hydrogen ion, hypoxanthine)	Training	Acute
Teece et al., 2021	M: 29	Rugby Union	Longitudinal	Wellness Questionnaire (HI) Sleep (total, efficiency, latency, wake episodes)	Training	Acute
Stepinski et al., 2020	F: 18	Soccer	Longitudinal	CMJ (peak power)	Training	Acute
de Freitas et al., 2015	M: 11	Futsal	Longitudinal	HRV (lnRMSSD) Sub-maximal exercise HR HRR	Training	Acute
Peacock et al., 2018	M: 8	Martial Arts	Longitudinal	Sleep (time, latency, efficiency, onset variances)	Training	Acute
Wisløff et al., 2004	M: 17	Soccer	Cross-sectional	CMJ (jump height)	Training	Acute and Chronic
Lim et al., 2021	M: 261 F: 79	Basketball	Cross-sectional	Wellness Questionnaire (PSQI)	Training	Acute
Dumortier et al., 2018	F: 7	Artistic Gymnastics	Longitudinal	Sleep (time)	Competition	Acute
Cunningham et al., 2016	M: 20	Rugby Union	Cross-sectional	CMJ (jump height) Drop Jump (contact time, RSI)	Training	Acute
Berriel et al., 2020	M: 13	Volleyball	Longitudinal	Wellness Questionnaire (RESTQ-Sport)	Training	Acute
Smart et al., 2008	M: 23	Rugby Union	Longitudinal	Biomarker (blood CK)	Competition	Acute
Ravé et al., 2020	M: 14	Soccer	Longitudinal	HRV (RMSSD)	Competition	Acute
Landolsi et al., 2014	M: 23	Shot Put	Cross-sectional	CMJ (jump height)	Training	Chronic
Brown et al., 2021	M: 21	Hockey	Cross-sectional	Biomarker (salivary C, DHEA, C:DHEA)	Competition	Acute
João R Silva et al., 2013	M: 13	Soccer	Longitudinal	CMJ (FT:CT)	Competition	Chronic
Carlsson et al., 2012	M: 12	Cross-Country Skiing	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Competition	Chronic
Young et al., 2011	M: 23	ARF	Cross-sectional	CMJ (jump height, peak force, peak velocity, peak power)	Training	Acute
Silva et al., 2021	M: 24	Soccer	Longitudinal	CMJ (jump height)	Training and Competition	Acute and Chronic

Loturco et al., 2019	M & F: 61	Athletics, Soccer, Rugby Sevens, Bobsled	Cross-sectional	CMJ (jump height) Squat jump (jump height)	Training	Acute
Jürimäe et al., 2006	M: 11	Rowing	Longitudinal	Biomarker (T, C, insulin, GH)	Training	Chronic
Casanova et al., 2020	F: 18	Soccer	Longitudinal	Biomarker (salivary C, T, T:C)	Competition	Acute and Chronic
Crewther, Potts, et al., 2018	M: 24	Rugby Union	Longitudinal	Biomarker (T, C)	Competition	Chronic
Boullosa et al., 2013	M: 8	Soccer	Longitudinal	HRV (CV RMSSD, RMSSD, SD1)	Training	Acute
Mancha-Triguero et al., 2021	F: 10	Basketball	Cross-sectional	Abalakov Test (time, height, impulse) Multi-Jump Test (average time)	Competition	Chronic
Rowell et al., 2018	M: 23	Soccer	Longitudinal	CMJ (FT:CT) Biomarker (salivary C, T, T:C)	Competition	Acute
Chrismas et al., 2019	M: 16	Soccer	Longitudinal	HRV (lnRMSSD)	Training	Acute
Araújo et al., 2019	M: 16 F: 16	Soccer	Cross-sectional	Sub-maximal exercise HR	Training	Acute
Ganzevles et al., 2017	M: 5 F: 8	Swimming	Longitudinal	HRR	Training	Acute
Dubois et al., 2020	M: 14	Rugby Union	Longitudinal	Biomarker (blood CK, CRP, T, T:C, RBC, lymphocytes, insulin growth factor, alanine, aspartate aminotransferase) CMJ (jump height) Wellness Questionnaire (RESTQ-Sport)	Training and Competition	Acute and Chronic
Elloumi et al., 2012	M: 16	Rugby Sevens	Longitudinal	Wellness Questionnaire (fatigue)	Training	Acute
Ihsan et al., 2017	M: 12	Hockey	Longitudinal	Wellness Questionnaire (fatigue, soreness, mood, sleep)	Competition	Acute
Northeast et al., 2019	M: 26	Soccer	Cross-sectional	CMJ (jump height, peak power, unilateral asymmetry score) IMTP (peak force, RFD, force at 100 ms) Drop Jump (contact time, jump height, stiffness, RSI)	Training	Acute
Vervoorn et al., 1992	F: 6	Rowing	Longitudinal	Biomarker (blood C, T, free T, free T:C)	Training	Acute
Siart et al., 2017	M: 8 F: 10	Athletics	Longitudinal	Biomarker (salivary T, C)	Competition	Acute
Malone, Mendes, et al., 2018	M: 30	Soccer	Longitudinal	Biomarker (blood CK) CMJ (jump height)	Training	Acute
Oliveira et al., 2020	M: 24	Soccer	Longitudinal	Wellness Questionnaire (HI)	Competition	Acute

Marcote-Pequeño et al., 2019	F: 19	Soccer	Cross-sectional	Squat Jump (jump height)	Training	Acute
Shalfawi et al., 2011	M: 33	Basketball	Cross-sectional	CMJ (jump height, peak power) Squat Jump (jump height, peak power)	Training	Acute
Rago et al., 2021	M: 15	Soccer	Longitudinal	Biomarker (blood T, C, T:C, CK, ferritin, iron, RBC, haemoglobin, haematocrit)	Training	Chronic
Beattie et al., 2021	M: 18	Soccer	Longitudinal	Biomarker (blood CK) CMJ (jump height, FT:CT, CT, FT, peak power, max force, take-off velocity, mean power, mean force)	Competition	Acute
Bootes, 2017	M: 8	Rowing	Longitudinal	CMJ (peak force, mean power, take-off peak force, peak power, eccentric / concentric duration) Squat Jump (peak power, concentric mean force)	Training	Acute
Mangine et al., 2014	M: 12	Basketball	Cross-sectional	Visual Reaction Time Motor Reaction Time Physical Reaction Time Variable Region Choice Reaction	Competition	Chronic
Malone, Owen, et al., 2018	M: 48	Soccer	Longitudinal	Wellness Questionnaire (soreness, sleep, fatigue, stress, energy)	Training	Acute
Troester et al., 2019	M: 27	Rugby Union	Longitudinal	CMJ (jump height, eccentric RFD)	Training	Acute
Díaz et al., 2013	M: 13	Swimming	Cross-sectional and Longitudinal	Biomarker (salivary C)	Competition	Acute
Buchheit et al., 2013	M: 18	ARF	Longitudinal	Biomarker (salivary C) Wellness Questionnaire (fatigue, sleep, soreness, stress, mood) Sub-maximal exercise HR	Training	Acute
Clemente et al., 2018	M: 13	Volleyball	Cross-sectional	Wellness Questionnaire (HI)	Training	Chronic
Crewther et al., 2013	M: 13	Rugby League	Longitudinal	Biomarker (salivary free T, free C)	Competition	Chronic
Springham et al., 2022	M: 18	Soccer	Longitudinal	Biomarker (salivary T, C, T:C)	Training and Competition	Chronic
Redman et al., 2021	M: 14	Rugby League	Cross-sectional	CMJ (jump height, concentric impulse, peak force, peak power)	Training	Chronic
Gonçalves et al., 2021	F: 22	Soccer	Cross-sectional	CMJ (jump height) Squat Jump (jump height) Hip / Groin Adduction and Abduction Test	Competition	Chronic
Saidi et al., 2020	M: 16	Soccer	Longitudinal	Biomarker (blood T, C, T:C)	Training	Acute

				Wellness Questionnaire (POMS)		
Merati et al., 2015	M: 13	Swimming	Cross-sectional	HRV (SD1, HFP)	Competition	Chronic
Veugelers et al., 2016	M: 38	ARF	Cross-sectional	HRR Sub-maximal exercise HR	Training	Acute
Rago et al., 2020	M: 17	Soccer	Longitudinal	Sub-maximal exercise HR	Training and Competition	Chronic
Rodríguez-Marroyo et al., 2017	M: 15	Cycling	Longitudinal	Sub-maximal exercise HR	Training	Acute
Ryan et al., 2021	M: 37	ARF	Longitudinal	Wellness Questionnaire (soreness, sleep, fatigue, stress, motivation) Hip / Groin Adduction and Abduction Test	Competition	Acute and Chronic
Scott et al., 2022	M: 19	Rugby League	Longitudinal	Sub-maximal exercise HR HRR	Training	Acute and Chronic
Berriel et al., 2021	M: 13	Volleyball	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Competition	Chronic
Stanković et al., 2022	F: 16	Soccer	Cross-sectional	CMJ (jump height) Squat Jump (jump height)	Training	Acute
Glassbrook et al., 2022	M: 16	Rugby League	Cross-sectional	CMJ (peak power, peak force)	Competition	Chronic
Selmi, Ouergui, et al., 2022	M: 15	Soccer	Longitudinal	Wellness Questionnaire (HI)	Training	Chronic
Silva et al., 2022	M: 25	Soccer	Longitudinal	Biomarker (CRP, albumin, haemoglobin, HDL, lymphocytes, RBC, basophils, eosinophil, potassium)	Training	Acute
Lu et al., 2022	M: 13 F: 10	Shooting	Longitudinal	Wellness Questionnaire (PSQI, POMS, CSAI-2)	Competition	Acute
Dobbin et al., 2020	M: 21 F: 20	Touch Football	Longitudinal	CMJ (jump height, peak power, peak force) Wellness Questionnaire (fatigue, mood, soreness, sleep, stress)	Competition	Acute
Lalor et al., 2020	M: 38	ARF	Longitudinal	Sleep (wake bouts, wake time, efficiency, latency)	Training	Acute
Salhi et al., 2022	M: 22	Soccer	Longitudinal	CMJ (jump height)	Training	Acute
Lourenço et al., 2023	M: 32	Soccer	Longitudinal	Wellness questionnaire (HI)	Training	Acute
Eastburn et al., 2022	M: 34	ARF	Longitudinal	Wellness questionnaire (sleep, fatigue, soreness, stress, mood)	Competition	Chronic
Barreira et al., 2022	F: 16	Soccer	Longitudinal	Sleep (efficiency, duration)	Training	Acute
Crewther, Hamilton, et al., 2018	F: 23	Hockey	Longitudinal	Biomarker (salivary T)	Competition	Acute
Rebelo et al., 2023	M:15	Volleyball	Longitudinal	CMJ (jump height, peak power)	Training	Acute

				Wellness questionnaire (fatigue, recovery, stress, soreness, sleep)		
Haksever et al., 2022	F: 39	Handball	Cross-sectional	Hip abduction test	Training	Acute

Note. AA alpha-amylase, *ACTH* adrenocorticotropic hormone, *ARF* Australian Rules Football, *BAM* Brief Assessment of Mood Questionnaire, *C:DHEA* cortisol to dehydroepiandrosterone ratio, *CK* creatine kinase, *CMJ* countermovement jump, *C* cortisol, *Core-CSD* Core Consensus Sleep Diary, *CRP* C-reactive protein, *CSAI 2-7* Competitive State Anxiety Inventory (2-7), *CT* contraction time, *CV RMSSD* coefficient of variation of root-mean-square difference of successive normal R–R intervals from time-domain analysis, *DHEA* dehydroepiandrosterone, *ESS* Epworth Sleepiness Scale, *F* female, *FT* flight time, *FT:CT* flight time to contact time ratio, *GH* growth hormone, *GHQ* General Health Questionnaire, *HDL* high-density lipoprotein, *HFP* high-frequency power, *HI* Hooper Index, *HR* heart rate, *HRR* heart rate recovery, *HRV* heart rate variability, *IgA* immunoglobulin A, *IMTP* isometric mid-thigh pull, *K+* potassium, *LDH* lactate dehydrogenase, *LDL* low-density lipoprotein, *lnHF* logarithmic high frequency power, *lnRMSSD* log-transformed root-mean-square difference of successive normal R–R intervals from time-domain analysis, *lnSD1* log-transformed standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots, *M* male, *ms* milliseconds, *n* sample size, *OSQ* Oviedo Sleep Questionnaire, *PCF* peak concentric force, *PCP* peak concentric power, *PEF* peak eccentric force, *PEP* peak eccentric power, *POMS* Profile of Mood States Questionnaire, *PSQI* Pittsburgh Sleep Quality Index, *RBC* red blood cells, *RESTQ-Sport* Recovery-Stress Questionnaire-Sport, *RFD* rate of force development, *RMSSD* root-mean-square difference of successive normal R–R intervals from time-domain analysis, *RSI* reactive strength index, *SCAT-A* Sport Competition Anxiety Test from A, *SD1* standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots, *SFMS* French Society for Sport Medicine Questionnaire, *SRSS* Short Recovery and Stress Scale for Sports, *STAI* State-Trait Anxiety Inventory, *T* testosterone, *T:C* testosterone cortisol ratio, *TQR* Total Quality Recovery Questionnaire, *VAS* Visual Analogue Scale, *WBC* white blood cells.

Reason for exclusion

Of the 759 studies for which the full text was reviewed, 594 were excluded from the qualitative synthesis (Figure 1). The two primary reasons for study exclusion were attributable to the failure to identify or analyse a relevant test and / or marker of athletic readiness (n = 109) or analyse a readiness test and / or marker with an appropriate performance measure (n = 202). Several studies analysed data from participants who failed this review's definition of an elite athlete and were excluded (n = 82). Studies which assessed the readiness marker and test following the performance measure (n = 43) were excluded, as were studies which applied a sport-specific test to assess athlete readiness (n = 27). Studies which reported elite and sub-elite athlete data concomitantly were excluded if the data from the elite athletic population could not be extrapolated independently (n = 24). Some studies analysed markers or tests of readiness across more than one season or 12-month period and were excluded (n = 24).

Risk of bias

Selection bias (in the form of random sequence generation and allocation concealment bias) was assessed as unclear or low risk for all included studies due to the nature of the study interventions. All studies were assessed as unclear or low risk of performance and detection bias, as the study designs did not require or address participant blinding.

Risk of attrition bias was assessed as unclear or low for all studies as they either did not address the wholeness of data, failed to report reasons for missing data or excluded participants, or the missing data from excluded participants were unlikely to relate to the true outcome. However, one study was assessed as potentially having a high risk of attrition bias with 26% of the original participants not included in the final analysis (Hooper et al., 1993).

Thirteen studies were assessed at high risk of reporting bias as they either reported only some of the correlations between the marker(s) or test(s) of readiness and the performance measure(s), or only the statistically significant correlations (Berriel et al., 2020; Bok & Jukić, 2019; Cormack et al., 2008; Doeven et al., 2019; R. Gathercole et al., 2015; Guilhem et al., 2015; Jürimäe et al., 2006; Mangine et al., 2014; Merati et al., 2015; Morales et al., 2019; Purge et al., 2006; Russell et al., 2021; Silva et al., 2014).

Participants

The studies included in this review reported on 3564 athletes, of which 2779 were male and 785 females, who submitted to a marker of athletic readiness prior to a subsequent measure of athletic performance. Of these studies, 115 investigated male athletes only, 28 investigated female athletes only, while 22 investigated a mixed sex cohort.

Study outcomes

From the 165 studies included in this review, a total of 20 different markers or tests of athletic readiness were identified across 46 sports (Table 1). The most common readiness markers and tests identified across the included studies were biomarkers (n = 58), CMJ (n = 58), wellness questionnaires (n = 42), SJ (n = 20), HRV (n = 14), sub-maximal exercise heart rate (n = 11), and sleep measures (n = 10).

73 studies implemented a longitudinal study design to assess the readiness measure and performance outcome relationship in an acute setting, 27 in a chronic setting, and 9 in a combined acute and chronic setting. 33 studies analysed the relationship between markers and tests of readiness and performance outcomes using a cross-sectional study design in an acute setting, 19 in a chronic setting, and two in a combined acute and chronic setting. One study used a combined longitudinal and cross-sectional study design to assess the readiness marker, performance outcome relationship in an acute setting, while one study implemented a longitudinal study design but failed to report the strength of the relationship between the performance measure and readiness marker (Silva & Paiva, 2016).

Meta-analysis

Table 1. Summary of acute markers and tests of athletic readiness included in the meta-analysis.

Readiness test / marker		**Performance measure**	**Studies (*n*)**	**Summary Correlation (*r*)**	**95% CI**	**Significance (*p*)**	**Heterogeneity (I^2)**
Cross-sectional studies							
CMJ	*Jump Height*	10 m sprint speed / time	6	0.69	0.47 to 0.83	.00	71.4%
	Peak Power	10 m sprint time	3	0.13	-0.10 to 0.35	.87	0.0%
Squat Jump	*Jump Height*	10 m sprint speed / time	3	0.70	0.48 to 0.84	.17	45.0%
Longitudinal studies							
CMJ	*Jump Height*	Total distance covered	3	0.38	0.12 to 0.59	.41	0.0%
Biomarker	*Salivary Cortisol*	Total distance covered	3	-0.01	-0.33 to 0.32	.99	0.0%
Exercise Heart Rate	*Sub-maximal*	Yo-Yo IR1 distance	3	-0.65	-0.78 to -0.47	.47	0.0%
HRV	*RMSSD + SD1*	Yo-Yo IR1 distance	5	0.66	0.44 to 0.80	.31	14.5%
	RMSSD	Competition load (sRPE)	3	0.10	-0.15 to 0.35	.91	0.0%

Note. CI confidence interval, *CMJ* countermovement jump, *HRV* heart rate variability, I^2 proportion of variance in observed effect due to variance in true effects, *m* metre, *n* sample size, *r* Pearson product-moment correlation coefficient, *RMSSD* root-mean-square difference of successive normal R–R intervals from time-domain analysis, *SD1* standard deviation of instantaneous beat-to-beat R–R interval variability from Poincare plots, *sRPE* session rating of perceived exertion, *Yo-Yo IR1,* Yo-Yo Intermittent Recovery Test Level 1.

From the 27 studies which satisfied the inclusion criteria (Balsalobre-Fernández et al., 2014; Beattie et al., 2021; Boraczyński et al., 2020; Boullosa et al., 2013; Buchheit et al., 2013; Coppalle et al., 2019; Costa et al., 2019; Costa et al., 2021; Cunningham et al., 2016; de Freitas et al., 2015; Dubois et al., 2020; Gonçalves et al., 2021; Hauer et al., 2020; Hulin et al., 2019; Loturco et al., 2018; Loturco, D'Angelo, et al., 2015; Malone et al., 2017; Moncef et al., 2012; Morales et al., 2019; Nakamura et al., 2020; Northeast et al., 2019; Peñailillo et al., 2015; Saidi et al., 2022; Shalfawi et al., 2011; Silva et al., 2021; Webster et al., 2022; Young et al., 2011), five markers and tests of athletic readiness were identified and meta-analysed: CMJ, biomarkers, SJ, sub-maximal exercise heart rate, and HRV. A summary of the acute and chronic, and longitudinal and cross-sectional study correlations of the readiness markers and tests with the relevant performance measures, are outlined in Tables 2 and 3.

Table 2. Summary of chronic markers and tests of athletic readiness included in the meta-analysis.

Readiness test / marker		Performance measure	Studies (*n*)	Summary Correlation (*r*)	95% CI	Significance (*p*)	Heterogeneity (I^2)
Cross-sectional studies							
CMJ	*Jump Height*	Maximal velocity	3	0.46	0.25 to 0.62	.57	0.0%
Longitudinal studies							
Biomarker	*Blood CRP*	Competition load (sRPE)	3	0.33	-0.04 to 0.56	.89	0.0%

Note. CI confidence interval, CMJ countermovement jump, CRP C-reactive protein, HRV heart rate variability, I^2 proportion of variance in observed effect due to variance in true effects, n sample size, r Pearson product-moment correlation coefficient, sRPE session rating of perceived exertion.

Countermovement jump

Figure 2 shows the association between various indices of CMJ and athletic performance. Acute, cross-sectional assessment revealed a large, statistically significant correlation between CMJ jump height and faster 10 m sprint speed and time (r = 0.69; p = .00), which was affected by substantial statistical heterogeneity (I^2 = 71%). A small, non-significant correlation existed between CMJ peak power and 10 m sprint time (r = 0.13; p = .87). Acute and longitudinal assessment of CMJ jump height found a non-significant, moderate association with total distance covered (r = 0.38; p = .41). Chronic, and cross-sectional CMJ jump height had a moderate, non-significant correlation with maximal speed (r = 0.46; p = .57).

Biomarkers

An acute, longitudinal assessment of salivary cortisol revealed a statistically non-significant, negative, and trivial association with total distance (Figure 3; r = -0.01; p = .99). When assessed over a chronic timeframe, blood C-reactive protein (CRP) exhibited a moderate but non-significant correlation with competition load quantified by sRPE (Figure 3; r = 0.33; p = .89).

Squat jump

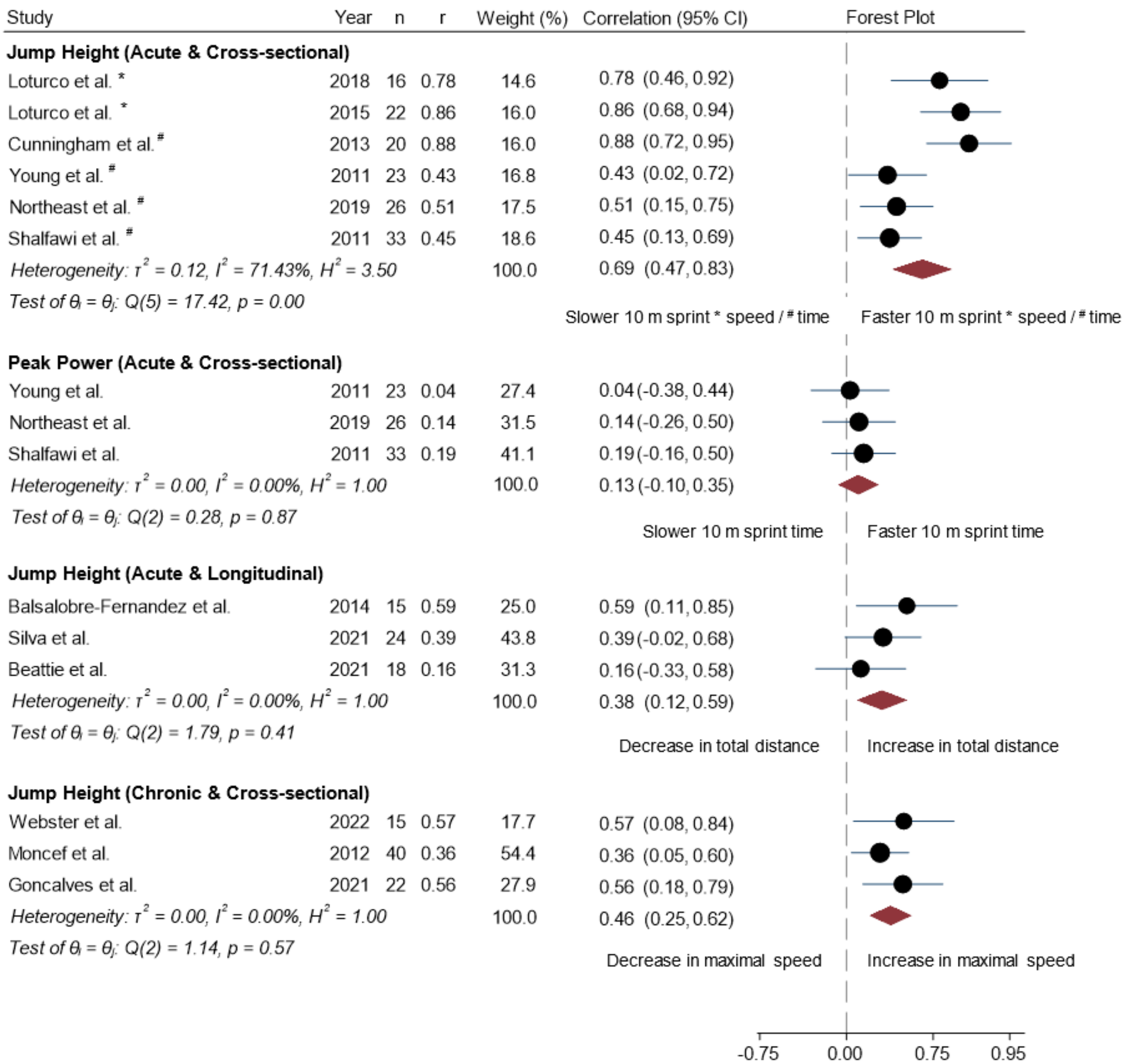
Cross-sectional and acute assessment of jump height from SJ provided a very large, but statistically non-significant correlation with 10 m sprint speed and time (Figure 4; r = 0.70; p = .17), which was affected by moderate statistical heterogeneity (I^2 = 45%).

Sub-Maximal Exercise Heart Rate

Acute and longitudinal assessment of sub-maximal exercise heart rate revealed a negative and large, but statistically non-significant, correlation with Yo-Yo IR1 distance (Figure 5; r = -0.65; p = .47).

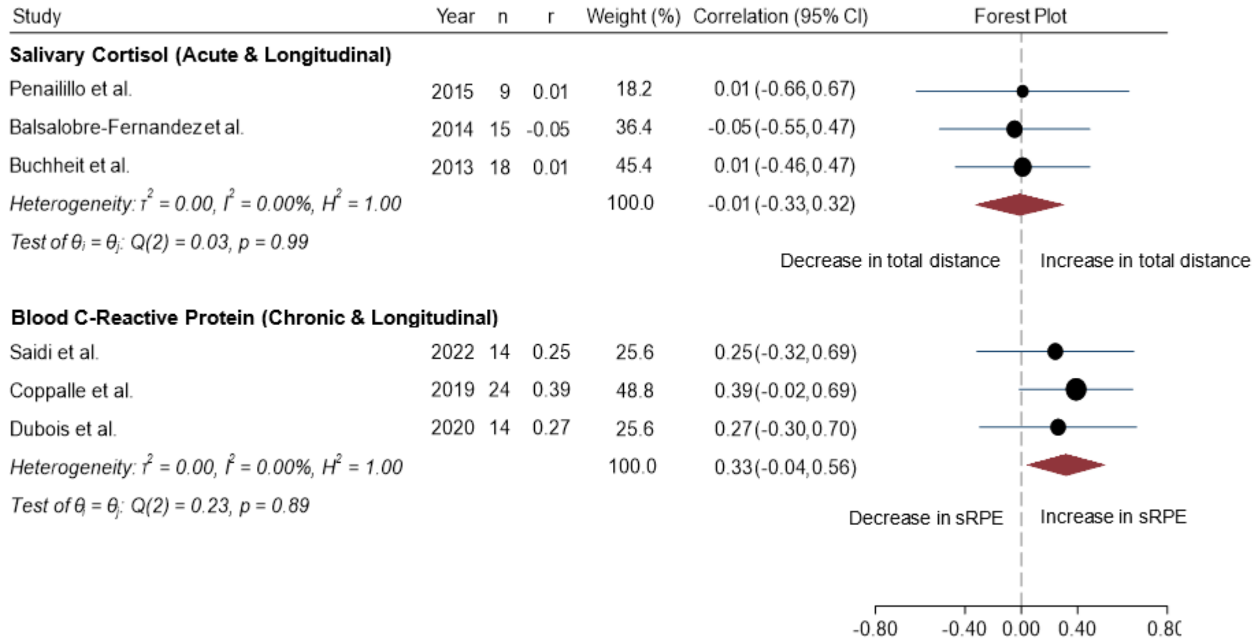
Heart Rate Variability

Figure 6 provides the correlation of acute and longitudinal assessment of RMSSD and SD1 indices of HRV and subsequent athletic performance. Pooled RMSSD and SD1 exhibited a large, but statistically non-significant, correlation with Yo-Yo IR1 distance (*r* = 0.66; *p* = .31), while a small, non-significant correlation was found between RMSSD and competition sRPE load (*r* = 0.10; *p* = .91).



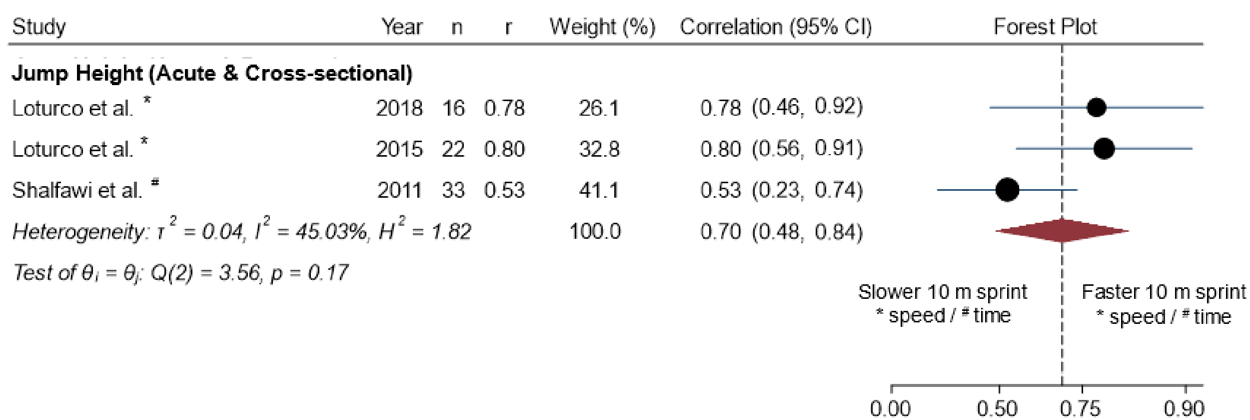
Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient.

Figure 2. Correlation of CMJ indices (using static arm position) and athletic performance measures.



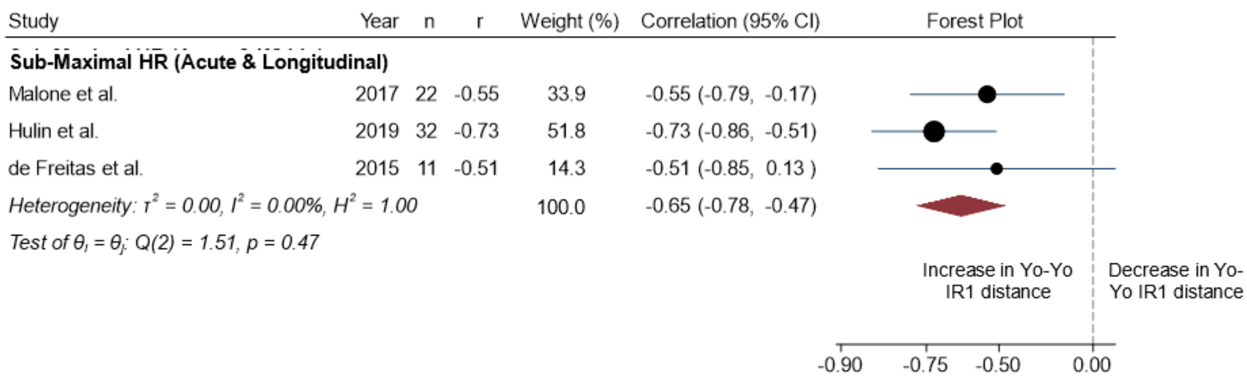
Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient, sRPE session rating of perceived exertion derived from competition.

Figure 3. Correlation of salivary cortisol and blood C-reactive protein biomarkers and athletic performance measures.



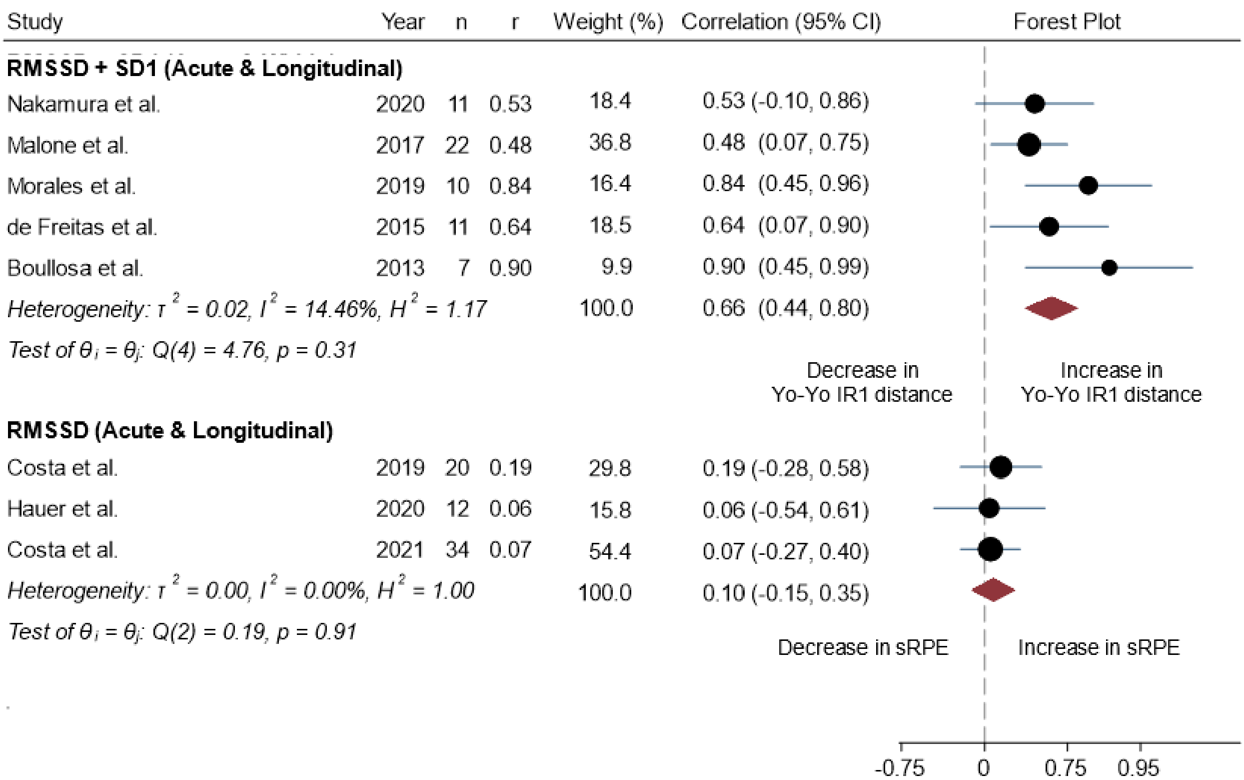
Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient.

Figure 4. Correlation of squat jump height (with hands on hips) and 10 m sprint speed and time.



Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient, Sub-Maximal HR, Sub-Maximal Exercise Heart Rate, Yo-Yo IR1, Yo-Yo Intermittent Recovery Test Level 1.

Figure 5. Correlation of sub-maximal exercise heart rate and yo-yo IR1 distance.



Note. CI confidence interval, n number of studies, r Pearson product-moment correlation coefficient, sRPE session rating of perceived exertion derived from competition, Yo-Yo IR1 Yo-Yo Intermittent Recovery Test Level 1.

Figure 6. Correlation of heart rate variability indices RMSSD and SD1, and athletic performance measures.

DISCUSSION

This systematic literature review explored the relationship between tests and markers of athletic readiness and subsequent performance in elite athletes. To the knowledge of the authors, no review has provided a combined, holistic assessment of the psychological and physiological readiness markers and tests to assess training status in elite team and individual sport athletes, while using correlation analysis to assess athletic performance (to best evaluate the sensitivity of the readiness measures). The 165 studies included in this review identified 20 markers and tests of athletic readiness, of which five measures were meta-analysed across 27 studies. The most common measures of athletic readiness were biomarkers, CMJ and wellness questionnaires. The most significant finding from this review was the validation of jump height from CMJ (without arm swing) to predict explosive leg muscle function, expressed as acceleration and speed qualities, in elite athletes. The five markers and tests of readiness included in the meta-analysis are discussed independently below.

Countermovement jump

This review found a large, positive correlation between an acute and cross-sectional assessment of jump height from CMJ (without arm swing) and superior 10 m sprint speed and time (Figure 2), which may have been impacted by substantial statistical heterogeneity. Interestingly, an increase in jump height when assessed in different contexts (i.e., chronic and cross-sectional, and acute and longitudinal designs), did not correlate to greater maximal speed or total distance in training and competition (Figure 2). Similarly, the acute and cross-sectional assessment of peak power from CMJ did not correlate with 10 m sprint time (Figure 2).

As a monitoring tool for leg muscle function, the CMJ remains the most utilised vertical jump test for practitioners to provide a practical measure of neuromuscular fatigue and recovery time from training and competition demands (Alba-Jiménez et al., 2022). As a measure of physical performance, the CMJ provides an assessment of the explosive qualities of the leg muscles (Young et al., 2011). Whilst modern technologies assessing CMJ provide numerous variables of interest, jump height is still the most commonly assessed variable (Taylor et al., 2012), which is in keeping with the findings of this review (Table 1). Yet standardisation of the CMJ is influenced by a number of factors including the depth of countermovement, use of arm swing, as well as the number and frequency of jumps used for analysis (Alba-Jiménez et al., 2022). However, comparison of the "*highest*" and "*average*" CMJ results found the use of an "*average*", in comparison to the "*best*" jump, to be more sensitive in identifying fatigue or the positive effects of supercompensation (Claudino et al., 2017).

Whilst the studies meta-analysed in this review were controlled for the use (or not) of arm swing, the depth of countermovement and varying number and frequency of jumps used in the analysis could not be controlled. These methodological variances may explain the substantial statistical heterogeneity found for jump height, and potentially the non-significant findings found for all CMJ variables other than jump height. Interestingly, acute and longitudinal, and chronic and cross-sectional, assessment of CMJ jump height was not correlated with increases in total distance and maximal speed respectively (Figure 2). These findings potentially suggest jump height is sensitive to various study designs, as well as assessment in the context of different physical performance measures.

In keeping with the significant finding from this review, previous studies with an identical study design also found statistically significant correlations between jump height from CMJ as a predictor of various speed and power qualities in elite soccer (Bosco et al., 1996), rugby league (West et al., 2011), athletics (Loturco et al., 2019), and surfing (Secomb, Lundgren, et al., 2015) athletes. Interestingly, a number of studies which implemented an identical acute and cross-sectional study design to this review, found a statistically significant correlation between CMJ jump height and 5 m sprint time (Boraczyński et al., 2020), 20 m sprint time (Northeast et al., 2019; Shalfawi et al., 2011), and 40 m sprint time (Shalfawi et al., 2011), but not for peak power. These previous findings are in keeping with the results from this review and supports the notion of a potential inverse relationship between jump height and peak power from CMJ, as a predictor of acceleration and power qualities in elite athletes.

Whilst this review validates the acute, cross-sectional assessment of jump height from CMJ (without arm swing) to predict acceleration and power qualities in elite athletes, caution should be used in the application of other CMJ variables and study designs to predict similar athletic qualities. In particular, the use of peak power from CMJ to predict 10 m sprint time, as well as the application of acute and longitudinal, and chronic and cross-sectional assessments of jump height to predict total distance and maximal speed, respectively.

Biomarkers

Despite finding biomarkers to be the most extensively investigated readiness measure in elite athletes (Table 1), neither of the biomarkers meta-analysed in this review were found to have a significant relationship with their respective performance measure. Specifically, a longitudinal assessment of acute, salivary cortisol and chronic, blood derived CRP, were not correlated with subsequent distance covered or competition load quantified by sRPE, respectively (Figure 3).

Cortisol is one of the most commonly used biochemical stress hormones to evaluate athlete response to recovery, workload, and training and competition stress (Edwards et al., 2018a). Whilst previous studies have established an association between salivary cortisol and subsequent competition performance variables in netball (Russell et al., 2021), triathlon (Balthazar et al., 2012), rugby union (Crewther, Potts, et al., 2018), soccer (Springham et al., 2022) and athletics (Balsalobre-Fernández et al., 2014; Siart et al., 2017), the application of cortisol as a marker to ascertain a change in performance remains ambiguous (Greenham et al., 2018). Similarly, and in keeping with the findings from this review, the majority of research in ARF (Buchheit et al., 2013; Cormack et al., 2008), soccer (Casanova et al., 2020; Peñailillo et al., 2015), rugby league (Crewther et al., 2013; McLellan et al., 2010), rugby union (Crewther et al., 2009; Gaviglio et al., 2014; Tiernan et al., 2020), track and field (Balsalobre-Fernández et al., 2014; Guilhem et al., 2015), swimming (Díaz et al., 2013), hockey (Brown et al., 2021), and powerlifting (Le Panse et al., 2010) athletes, found no association between salivary cortisol and various measures of athletic performance.

It has been postulated salivary cortisol is not sensitive to total volume and lower intensity performance measures (i.e., total distance) in professional soccer (Peñailillo et al., 2015), offering a potential explanation for the non-significant correlation found in this review. This suggests the use of salivary cortisol may be best utilised as a readiness marker to predict higher intensity performance measures which evoke a greater stress response. Whilst this relationship requires further investigation to be validated, this hypothesis is supported by studies in elite netball (Russell et al., 2021) and soccer (Springham et al., 2022) athletes which found pre-competition salivary cortisol to be significantly, positively associated with subsequent "*higher intensity*" change of direction and high-speed running measures, respectively.

A consequence of intense training and competition stress commonly induces an inflammatory response in the body, often presenting as swelling and muscle soreness, and results in decreased muscle function and the leakage of muscle protein such as CRP (Chatzinikolaou et al., 2010; Hirose et al., 2004). Given its link to acute inflammation, CRP is considered an important measure to provide information regarding the severity of the trauma or injury precipitating the inflammatory processes (Coppalle et al., 2019; Joao R Silva et al., 2013). Yet the validity of pre-training or competition CRP as an indicator of performance in elite athletes has not been widely investigated outside of soccer and rugby union, with few significant correlations between blood CRP and ensuing athletic performance (Coppalle et al., 2019; Dubois et al., 2020; Saidi et al., 2022; Silva et al., 2022).

The non-significant correlation found in this review between blood CRP and chronic, competition load is potentially explained by the passage of time between the assessment of CRP relative to the competition load.

It has been established that CRP returns to baseline levels in elite team-sport athletes within two days following competition (37 hours) (Souglis et al., 2015). Therefore, unless the recovery period between the preceding competition / training stimulus and the subsequent activity is appropriate (i.e., less than 37 hours), then it is conceivable a pre-competition measure of CRP has no relationship to competition load. Whilst future research should look to investigate this relationship further, practitioners should apply caution when using CRP as a marker of readiness more generally, but particularly in circumstances when the duration of recovery between training or competition is insufficient to allow the homeostatic restoration of inflammation (less than 37 hours).

Squat jump

This review highlights the relative lack of research in the application of squat jump variables to homogenous performance measures. Whilst 20 studies evaluated squat jump variables in the context of a subsequent measure of athletic performance (Table 1), only three studies assessed jump height from squat jump using an analogous study design and performance measure. These studies were meta-analysed using a standardised, acute, and cross-sectional squat jump protocol, in which participants kept their hands on their hips throughout the jump. Despite the level of standardisation, no significant correlation was observed between jump height and 10 m sprint speed and time (Figure 4).

This finding provides mixed support for previous studies assessing the relationship between jump height from SJ and subsequent athletic performance. The current finding complements an existing body of literature which found no association between SJ jump height and various training and competition performance outcomes in elite karate (Loturco et al., 2014), basketball (Pojskic et al., 2018), surfing (Secomb, Farley, et al., 2015), soccer (Gonçalves et al., 2021; Saidi et al., 2020; Saidi et al., 2022; Saidi et al., 2019; Stanković et al., 2022), cross-country skiing (Carlsson et al., 2012), and track and field (Loturco et al., 2019) athletes. Conversely, studies have found a positive correlation between jump height from squat jump and performance outcomes in elite track and field (Loturco, Pereira, et al., 2015; Loturco et al., 2019), basketball (Pojskic et al., 2018), handball (Moncef et al., 2012), soccer (Emmonds et al., 2019; Gonçalves et al., 2021; Marcote-Pequeño et al., 2019; Stanković et al., 2022), surfing (Secomb, Lundgren, et al., 2015), and volleyball (Berriel et al., 2021) athletes. Clearly, the current finding contributes to the ambiguity around the sensitivity of SJ jump height to predict athletic performance, whilst also inadvertently supporting the suggestion alternate SJ variables of mean force, mean power and relative mean power should be preferred, as they exhibit acceptable reliability and sensitivity (Edwards et al., 2018b).

Interestingly, the current finding is also in contrast with an earlier finding of this review for CMJ jump height, despite an identical, standardised testing protocol and performance measure. Whilst both findings were affected by statistical heterogeneity, the contrasting findings are possibly explained by several other factors. Firstly, the use of different technologies to measure jump height (i.e., contact mat or force platform), as well as the sensitivity of the inherent physiological and biomechanical differences of each jump (Van Hooren & Zolotarjova, 2017), particularly the performance enhancing effect of the stretch-shortening cycle from the countermovement (McGuigan et al., 2006). Further, the smaller sample of studies used to meta-analyse the association between jump height from SJ and the performance outcome, is also a likely contributing factor.

While squat jump assessment more broadly is considered a simple, practical, valid and reliable tool for measuring neuromuscular function (R. J. Gathercole et al., 2015) and explosive power output from the lower limbs (Markovic et al., 2004), the current finding suggests practitioners should exhibit caution when using SJ jump height as a monitoring tool of the lower limbs to predict acceleration and power performance in elite athletes.

Sub-Maximal Exercise Heart Rate

This review found 11 studies which evaluated the use of sub-maximal exercise heart rate to forecast athletic performance (Table 1). Three studies were meta-analysed, which found no association between the acute, longitudinal assessment of sub-maximal exercise heart rate and greater Yo-Yo IR1 performance (Figure 5).

This finding is inconsistent with previous cross-sectional assessments in studies investigating sub-maximal heart rate, which found significant correlations with Yo-Yo IR1 (Ingebrigtsen et al., 2014) and Yo-Yo IR2 performance (Ingebrigtsen et al., 2014; Veugelers et al., 2016). This inconsistency in findings may be attributable to the sensitivity of sub-maximal heart rate assessment to the type of study design (longitudinal or cross-sectional assessment). This explanation would appear consistent with the likelihood of longitudinal assessment of sub-maximal exercise heart rate being accentuated and influenced by day-to-day variability in heart rate and environmental factors (Juul & Jeukendrup, 2003). Previous studies have also found the assessment of other maximal aerobic performance measures such as total competition and training distance, to have small to large correlations with sub-maximal heart rate (Buchheit et al., 2013; Rago et al., 2020). Ultimately, this suggests sub-maximal heart rate may also be sensitive to various measures of athletic performance.

Heart rate assessment at a fixed, sub-maximal intensity is commonly used as an indicator of training status in elite athletic populations and is a valid and reliable tool to assess Yo-Yo IR2 performance in elite Australian rules football players (Veugelers et al., 2016). This review's non-significant finding emphasises the need for practitioners to ensure their sub-maximal exercise heart rate assessment protocol is sensitive to their specific performance outcome. The contrasting finding from this review with previous studies (Ingebrigtsen et al., 2014; Veugelers et al., 2016), cautions the use of a longitudinal assessment of sub-maximal heart rate to predict an elite athlete's capacity to perform intense, intermittent exercise assessed by Yo-Yo IR1 performance (Bangsbo et al., 2008). This adds further support to the existing literature that a cross-sectional assessment of sub-maximal heart should perhaps be preferred as a measure of training status in elite athletes to predict maximal aerobic capacity.

Heart Rate Variability

Of the 14 studies which assessed pre-training and competition HRV, eight studies implementing a longitudinal study design were meta-analysed across two different performance outcomes (Table 1; Figure 6). This review found an acute, pre-training and competition HRV assessment of pooled RMSSD and SD1, and RMSSD measures separately, were not correlated with subsequent Yo-Yo IR1 distance and competition load quantified by sRPE (Figure 6).

The use of HRV assessment as a non-invasive measure of autonomic nervous system status in response to training and competition stress is common practice in elite sport (Plews et al., 2014). The current application and interpretation in the literature of HRV assessment as a readiness marker offers mixed support for the findings of this review, particularly in studies with an acute, longitudinal study design. In support of this review's findings, a previous study in elite male futsal players using a similar performance measure in Yo-Yo IR2 distance, also failed to find a statistically significant correlation with resting HRV (de Freitas et al., 2015). Similarly, other studies assessing the correlation between HRV, and training and match derived physical output data in elite male Gaelic football and female soccer players, were unable to find significant associations (Costa et al., 2019; Malone et al., 2017). However, some studies found statistically significant correlations between resting HRV assessment and physical output data from training (Thorpe et al., 2015) and Cooper 12-minute run test performance (Morales et al., 2019) in elite soccer athletes. It has been suggested such ambiguous findings in the literature may be attributable to methodological inaccuracies due to the large variation in day-to-day HRV measurements (Plews et al., 2014), offering a potential explanation for the contrast in findings between this review and existing research.

The assessment of HRV can be influenced by a myriad of complex environmental, lifestyle, physiological, neuropsychological and non-modifiable (i.e., gender and age) factors (Fatisson et al., 2016). The confounding influences on HRV assessment potentially explains the non-significant findings from this review and highlights the importance of ensuring standardised HRV measurements, despite the inherent difficulties of doing so in a team sport setting. However, the findings from a previous review found vagal-related HRV indices increased in response to positive training adaptations which is suggestive of HRV being a sensitive marker of readiness, albeit in the absence of a standardised performance outcome (Bellenger et al., 2016). Therefore, the application of this review's findings for practitioners cautions the use of resting, pre-training HRV assessment as a sensitive marker of readiness in predicting aerobic capacity in elite athletes, specifically for Yo-Yo IR1 performance and subjective competition load.

Limitations

Evidenced by the volume of studies included in this review and summarised in Table 1, this review is limited by the amount of data which could be extracted from eligible studies, particularly those included in the meta-analysis. The lack of standardisation in the application of markers and tests of athletic readiness, and the outcome correlation, to common and consistent performance measures in the included studies, limited the depth of findings and analysis in this review. However, it is acknowledged the application of markers and tests of readiness to assess athletic performance is largely determined by the contextual physiological and psychological requirements of the sport. As such, the assessment and application of various readiness markers and tests with consistent and standardised performance measures may not be appropriate in practice.

This review acknowledged the methodological differences and variations in the application of various measures of readiness, particularly the assessment of HRV and sub-maximal exercise heart rate (Plews et al., 2014). These inconsistencies potentially limit the generalisability of this review's findings, particularly given the known sensitivities associated with the markers and tests of readiness identified in this review. Whilst the strict standardisation of studies eligible for inclusion in the meta-analysis intended to account for this limitation, this confounder ultimately reduced the number of studies eligible to be meta-analysed.

CONCLUSIONS

This review sought to investigate the validity of tests and markers of athletic readiness to predict subsequent athletic performance in elite athletes. In examining this relationship, 20 athletic readiness markers and tests were identified, with the requisite level of data from five readiness measures meta-analysed. The most common measures employed to assess athletic readiness in elite athletes includes the assessment of biomarkers, CMJ testing and the use of subjective wellness questionnaires.

The most significant finding from this review is the validation of the use of jump height from CMJ (without arm swing) to predict power and acceleration qualities in elite team and individual sport athletes, where explosive leg muscle function is an integral physical requirement of the sport. However, there was no significant relationship between additional measures of readiness, in the form of salivary cortisol and blood CRP biomarkers, SJ, sub-maximal exercise heart rate, indices of HRV, and subsequent athletic performance. It is suggested, when implementing these readiness measures as part of an athlete monitoring system, that practitioners ensure their validity with the relevant performance outcome(s).

It is postulated this review's non-significant findings are explained by the sensitivity of different study designs, the application of different performance measures, and the methodological differences in the assessment of the various tests and markers used to assess athletic readiness. Whilst this review has somewhat contributed to the ambiguity in the literature, and uncovered conflicting findings in the current evidence, the findings highlight the sensitivities of the inter and intra-individual variations between athletes which likely influences the validity of some measures identified in this review. However, further research into, and standardisation of, these markers and tests of readiness is required to ensure their sensitivity and validity to contextualised measures of subsequent athletic performance in elite team and individual sport athletes.

AUTHOR CONTRIBUTIONS

SJJ designed and conceptualised the research question and method of analysis, conducted the systematic search, screened all articles, extracted and analysed the data, and prepared the manuscript. PCB designed and conceptualised the research question and method of analysis, assisted with the analysis and interpretation of data, and substantively revised the manuscript. DJB designed and conceptualised the research question and method of analysis, assisted with the analysis and interpretation of data, and substantively revised the manuscript. GKB screened all articles and confirmed the data extraction and risk of bias assessment of the lead author. CRB designed and conceptualised the research question and method of analysis, assisted with the analysis and interpretation of data, and substantively revised the manuscript. All authors read and approved the final manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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APPENDIX

Supplementary Table 1. Systematic review master search strategy.

1. Athletes/ and (high perform* or professional* or olympic or Olympian* or competit* or elite) OR ((high perform* or professional* or olympic or Olympian* or competit* or elite) and (sportspe* or sportswo* or sportsm* or athlete* or player*))

AND

2. gait/ OR gait analysis/ OR gait OR Biomarkers/ OR Lactic Acid/ OR Urea/ OR Creatine Kinase/ OR Norepinephrine/ OR Catecholamines/ OR Epinephrine/ OR Cytokines/ OR Immunoglobulin/ OR alpha-Amylases/ OR Glutamine/ OR Testosterone/ OR Hydrocortisone/ OR lymphocyte count/ OR Neutrophils/ OR Hormones/ OR (biomarker* or bio marker* or cortisol hormone* or endocrine* or lactic acid or creatine kinase or CK or urea or norepinephrine or catecholamine* or epinephrine or cytokine* or biological marker* or biochemical marker* or immunoglobulin or IgA or alpha-Amylase* or alpha Amylase* or physiological marker* or immunoendocrine marker* or glutamine or glutamate or physiological measure* or testosterone or hydrocortisone or lymphocyte count* or neutrophil* or hormone*) OR (countermovement jump or counter movement jump or CMJ or vertical jump or run* pattern* or isometric midthigh pull or isometric mid-thigh pull or isometric mid-thigh pull or ISMTP or flight time to contraction time or flight time to contraction ratio or FT:CT or adductor strength assessment or eccentric hamstring strength assessment or adductor strength test or hamstring strength test or hamstring strength assessment or groin squeeze strength test or groin squeeze strength assessment) OR Heart Rate/ OR Sleep/ OR sleep hygiene/ OR (heart rate or heartrate or HR or HRV or HRR or sleep or yo-yo intermittent recovery or yoyo intermittent recovery or submaximal heart rate assessment or sub-maximal heart rate assessment or submaximal heart rate test or sub-maximal heart rate test) OR Reaction Time/ OR ((reaction or response) adj (speed* or tim* or laten*)) OR (choice response or rating of perceived exertion or RPE or perceptual wellness questionnaire* or perceived wellness or recovery stress questionnaire* or recovery cue or athlete burnout questionnaire or athlete distress questionnaire or daily analysis of life demands for athletes) OR Exercise Test/ OR (exercise test* or fitness test*)

AND

3. Fatigue/ OR Muscle Fatigue/ OR fatigue* OR Athletic Performance/ OR Psychomotor Performance/ OR (((athlete* or psychomotor or physical or fitness or competit*) adj2 Perform*) or training status) OR recove* OR Physical Endurance/ OR Endurance Training/ OR Resistance Training/ OR Muscle Strength/ OR (endurance or stamina or overtraining or over training or over reach* or overreach* or prepare* or readiness or endurance training or resistance training or power training or strength training or motor learning training or muscle strength).

SCIENTIFIC
JOURNAL OF
SPORT AND
PERFORMANCE

ORIGINAL ARTICLE

Correlation effects of self-regulation on academic performance and self-efficacy in college physical education MOOC learning

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ABSTRACT

At present, MOOCs have gradually become a part of daily teaching in colleges and universities, but domestic physical education curriculum research has not yet covered the content of the relationship between college students' learning self-regulation, self-efficacy, and physical education performance in the MOOC learning environment. Therefore, it is necessary to study the correlation between self-regulation and self-efficacy in the study of physical education MOOCs through a questionnaire survey and analysis of 52 college students majoring in physical education at a BSU university in Beijing. The study found that there is a significant correlation between self-regulation and academic performance, but the impact of self-efficacy on academic performance is not significant, and the relationship between self-regulation and self-efficacy needs to be further explored.

Keywords: Physical education, MOOC, Self-regulation, Self-efficacy.

Cite this article as:
Bahir, H., & Xiaoyun, W. (2023). Correlation effects of self-regulation on academic performance and self-efficacy in college physical education MOOC learning. *Scientific Journal of Sport and Performance*, *2*(3), 395-401. https://doi.org/10.55860/KGHP5564

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Submitted for publication May 24, 2023.
Accepted for publication June 05, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/KGHP5564

INTRODUCTION

With the deepening of the "*Internet* +" era, the role of Massive Open Online Courses (MOOCs) in promoting the overall reform of education and restructuring the educational ecosystem has become increasingly prominent, and college physical education is no exception (Chang et al., 2022). Compared with the traditional teaching mode, the MOOC platform opens up the course learning content, promotes the sharing of excellent educational resources, and better reflects the principle of teaching students in accordance with their aptitude and fairness in teaching (Venitz & Perels, 2019). However, some experts and scholars have also found that the application effect and influence of MOOCs in college physical education courses are not as good as expected (Dembo & Seli, 2004). Many theoretical approaches have emphasized that the effectiveness and impact of MOOC courses are influenced by self-regulation and self-efficacy, and traditionally successful college students are often described as "*self-regulation and management students*". Educational research involving MOOCs at home and abroad often focuses on the promotion of self-regulation in the MOOC learning environment, with the purpose of analyzing whether self-regulation affects academic performance and learners' learning self-efficacy (Milligan & Littlejohn, 2016). Empirical studies in other disciplines such as mathematics and foreign languages have proved that the MOOC learning of the above subjects is affected by the learners' own self-regulation and self-efficacy, and the MOOC learning environment itself also has an impact on the learners' own self-regulation and self-efficacy. Influence. However, at present, there is no empirical analysis of relevant aspects of MOOC research on domestic physical education courses. Based on this, this study intends to investigate whether college students' physical education performance is affected under the MOOC learning environment and to explore the correlation between college students' learning self-regulation, self-efficacy, and physical education performance under the MOOC learning environment, with a view to providing a basis for college sports MOOCs. Provide research support for course application effects and influence enhancement (Milligan & Littlejohn, 2016).

Literature review

Flipped learning is a form of student-centered instruction in which students are in charge of studying the course materials in advance and taking part in activities that the teacher has planned for the class (Rosen et al., 2017). Flipped learning has recently received strong support from researchers in education from a variety of sectors. The training is moved to the pre-class activities so that the in-class activities, such role-playing, debates, quizzes, and group projects, may be more interactive and student-centered (Godoy Garraza et al., 2019). Incorporate several active learning techniques, such as recorded lectures, quizzes, and student participation in cognitive processes, into a blended learning course to create flipped learning (Zainuddin & Halili, 2016). We examined numerous flipped learning styles and the advantages of such classes. Additionally, they stated that contextual learning is crucial for healthcare and medical education since it offers opportunities for practice and circumstances where information can be applied (Godoy Garraza et al., 2019).

Numerous studies have demonstrated that students may benefit from being led into real-world situations by adopting effective teaching techniques. Students now have access to a variety of learning opportunities and resources thanks to the integration of educational technology into the classroom, enabling them to quickly find learning materials for practical scenarios (Muñoz-Merino, 2015). employed simulation learning techniques to assess student performance and allow students to conduct situational learning. In this environment, students encourage their classmates to apply their knowledge, foster creativity, engage in teamwork, study collaboratively, exercise critical thought, increase the efficacy of their learning, and acquire information and skills outside of their discipline (Chang et al., 2022). Self-regulated Learning (SRL) is a method of learning that calls for goal-setting, the application of techniques, self-monitoring, and self-adjustment. According to researchers, learners may use metacognition and motivational techniques to actively generate knowledge and increase their capacity for learning (Chang et al., 2022). characterized SRL as students' self-generated ideas, perceptions, and planned activities for accomplishing their self-set objectives based on the assessment of and reflection on their own performances. This definition was included in a proposal for an SRL architecture. High-achieving students create specific learning objectives for themselves, employ more learning techniques during the learning process, self-supervise the learning process more frequently, and modify their learning rhythm in response to their outcomes, according to research on SRL (Wu et al., 2020). According to researchers, self-regulation is a conscious process that naturally shapes a person's behavior based on their motivation and is strongly linked to their long-term objectives or ideals (An et al., 2016).

OBJECTS AND METHODS

Object

A university student in Beijing. After excluding the causes of physical fitness and disease, this study randomly selected 52 college students from a BSU university in Beijing, majoring in physical education and training. Among the surveyed students, 28 boys and 23 girls were divided into a control group and an experimental group. A total of 52 questionnaires were distributed, and 51 valid questionnaires were recovered, for an effective recovery rate of 98.1%. All tests were conducted with the consent of those who filled out the questionnaires. The age of the subjects ranged from 17 to 21 years old, with an average age of 18.7 years.

Processes

The tastes in the control group and the experimental group all normally choose courses to study in the spring semester of the aerobics physical education course for college students. Different from the control group, the tastes in the experimental group studied in the MOOC learning environment, practiced independently after class, and took the test with the tastes in the control group after 16 weeks. In order to evaluate the self-efficacy of the tastes, a self-efficacy questionnaire was issued and filled out in the first week of the course, and after the 16-week physical education course was over, the final assessment of the aerobics physical education course was completed.

Questionnaire and survey content

1. Basic personal information, including subjects' age, height, weight, whether they have fitness habits, etc.
2. General Self-Efficacy Questionnaire (GSES) The Chinese version of the scale was compiled by Schwarzer et al. There are 10 test items in this form, which are mainly used to test the teste's judgment on the ability to cope with difficulties in daily life or study. Respondents rated themselves on a scale of 1–4. The Chinese version of GSES has good reliability and validity; its internal consistency coefficient Cronbach a = 0.87; test-retest reliability r = 0.83 ($p < .001$); and half-way reliability r = 0.82 (n = 40, $p < .001$).
3. Aerobics MOOC courses for college students the university's self-developed aerobics MOOC and assessment data are used as the basis for students' learning content and performance assessment.
4. Self-regulation. The subjects answered the question of whether to carry out self-regulation methods and efficacy as the basis for whether to carry out effective self-regulation in the process.

Data processing and analysis

This study uses the SPSS 26.0 social statistical analysis package for analysis.

RESULTS

Analysis of the basic situation of college students' self-efficacy in physical education MOOCs the self-efficacy scores of the college students under test were compared with the norms of existing college students (see Table 1). Overall, a normal sense of self-efficacy the self-efficacy scores of the control group and the experimental group were statistically analyzed, and the difference was not significant, indicating that there was no significant difference in the self-efficacy level between the experimental group and the control group, which met the requirements of random allocation and the effects brought about by MOOC learning and self-regulation. no change It is caused by individual reasons.

Table 1. Comparison of characteristics of college students' self-efficacy.

Item	Mean self-efficacy	Standard deviation	F	Sing.
Control group	1		2.395	.128
Test group	0.113	1		

Comparative analysis of college students' independent practice after class

Count the number of times students practice independently after class every week, and compare and analyze the situation of autonomous contact between the control group and the experimental group after class (see Table 2). The difference is not significant, indicating that both the experimental group and the control group can practice independently in order to complete the course requirements.

Table 2. Comparison of self-directed practice after class of college students (weeks).

Item	Number of exercises per week	Standard deviation	F	Sing.
Control group	1.944	1.944	0.401	.153
Test group	1.711	1.711		

The comparison of college students' aerobics examination results

Comparing the test scores of college students' final aerobics assessment (see Table 3), the average score of the experimental group is slightly higher than that of the control group, but the difference is not significant, indicating that MOOC teaching and traditional teaching in the aerobics course have a significant impact on There is no significant effect on students' test scores. The standard deviations of the assessment scores in the experimental group and the control group are both large, indicating that there are large differences between individual students in both the experimental group and the control group.

Table 3. Comparison of college students' aerobics assessment results.

Item	Test results	Standard deviation	F	Sing.
Control group	58.20	20.037	0.000	.998
Test group	62.96	21.310		

Analysis of the correlation between college students' self-regulation and physical performance

Correlation analysis was carried out on whether the college students were subjected to experimental treatment, self-efficacy, aerobics assessment results, and self-regulation (see Table 4), and there was no significant correlation between traditional teaching and MOOC teaching and self-efficacy, assessment scores, and self-regulation , there is no significant correlation between self-efficacy and assessment results and self-regulation; there is a significant correlation between self-regulation and assessment scores, indicating that whether students can self-regulate in the process of MOOC learning will affect the final assessment scores, and also That is to say, it will affect the effect of learning.

Table 4. Correlation between experimental treatment and self-efficacy, assessment performance and self-regulation (r).

Item	Experimental treatment	Self-efficacy	Test results	Self-regulation
Experimental treatment	1			
self-efficacy	0.113	1		
Test results	0.117	0.231	1*	
self-regulation	0.114	0.057	0.553**	1

*Note: *significantly correlated at .05 level (two-sided), **significantly correlated at .01 level (two-sided).*

DISCUSSION AND ANALYSIS

First of all, the self-regulation requirements of college students are very high in the study of physical education MOOCs. In the absence of a significant difference in self-efficacy, self-regulation directly affects the academic performance of college students. Compared with traditional physical education teaching, MOOCs lack teacher feedback, and students need to give feedback and adjust their own performance. There is no significant difference in self-efficacy between the experimental group and the control group, and the difference in performance between students does not come from self-discipline. difference in effectiveness Therefore, the level of self-regulation directly affects the academic performance of college students. Self-regulation helps students reflect on and adjust their behavior and actions. It also helps students adjust their actions, training methods, and training time in a timely manner. Without the assistance of teachers, self-regulation is necessary for students to achieve good academic performance through MOOC learning. Secondly, compared with traditional physical education teaching and learning, there is no research basis for the improvement of physical performance in physical education MOOC learning, and there is also no evidence of an obvious performance decline. Compared with traditional physical education teaching and learning, there is no significant difference in the performance of students studying physical education MOOCs, which shows that students can complete the requirements of physical education courses through a certain learning mechanism rather than only knowledge-based courses as traditionally believed. Skill-based courses are not suitable for MOOC learning. Therefore, for skill-based courses in physical education, on the basis that students meet certain conditions, teachers can use MOOC learning to more flexibly adapt to students' individual learning styles, complement traditional teaching methods, and meet students' learning needs. Finally, the test subjects of this study are college students majoring in physical education and training, and the research results may not be applicable to college students who are not majoring in physical education. Due to the particularity of skill-based physical education courses such as aerobics, it is still recommended for students who do not have a certain sports foundation to focus on traditional physical education teaching and learning to avoid sports injuries caused by blind training. The test subjects of this research are college students majoring in physical training. The students themselves have a certain sports foundation and master the self-regulation methods of physical exercise. The results of this study cannot be predicted or explained for college students who are not majoring in physical education. Further research is needed. Conduct investigations to draw more adaptive conclusions. In addition, the test in this study was carried out in the practical physical education class, and further research on the differences existing in the physical education theory class may be considered in the future.

CONCLUSION

Ordinary college students study physical education courses in a physical education MOOC learning environment, which requires high personal self-regulation. In the absence of a significant difference in self-efficacy, self-regulation directly affects the academic performance of college students. Training students to improve self-regulation Competence can improve the academic performance of learners in MOOC teaching environments.

AUTHOR CONTRIBUTIONS

Hizbullah Bahir; literature Review, research method and design, research analysis, and generally completed most of this research. Wang Xiaoyun; She collected the primary data and presented a general idea about the research.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

Secular trends in physical fitness and performance of university track and field athletes

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ABSTRACT

There are only few records of physical fitness data for athletes. This study aimed to explore the secular trends in physical fitness data of student athletes and the relationship of fitness parameters with the results of intercollegiate sports competitions. We used the physical fitness data of male students belonging to the Juntendo University Athletics Club from 1999 to 2019. The analysed parameters were height, weight, chest circumference, skinfold thickness, grip strength, vertical jump, sidestep, and sit and reach test. The ekiden results were examined in relation to data on medium- and long-distance activities with reference to the ranking. The study results suggested no difference in the skinfold thickness of the upper extremity across the events, except for throwing events. Grip strength declined gradually in sprints, hurdles, and jumping events, while it was high in throwing events. Vertical jump records declined over time in all events and remained at low levels in middle- and long-distance events. Sidestep improved among males in the general population, while it remained the same among all athletes. A relationship was found between grip strength and vertical jump, which are indices of muscle strength and power, and competitive results obtained in middle- and long-distance races.

Keywords: Performance analysis, Physical conditioning, Student athlete, Athletic performance, Grip strength, Vertical jump, Sit and reach test.

Cite this article as:
Matsumoto, Y., Kohmura, Y., Nakamura, A., Takanashi, Y., & Aoki, K. (2023). Secular trends in physical fitness and performance of university track and field athletes. *Scientific Journal of Sport and Performance*, *2*(3), 381-394. https://doi.org/10.55860/JZMZ6927

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Submitted for publication June 03, 2023.
Accepted for publication June 13, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/JZMZ6927

INTRODUCTION

Many studies have reported the relationship between physical fitness and performance in athletics (Loturco et al., 2019; Nuzzo et al., 2008). Events such as sprint (Maćkala et al., 2015; Loturco et al., 2015), middle- or long-distance races (Castillo-Domínguez et al., 2021; Yamanaka et al., 2019), jumps (Zushi et al., 2020; Inaoka et al., 1993), throws (Bouhlel et al., 2007; Terzis et al., 2007), and decathlons (Reuter et al., 2017; Yoshioka et al., 2010) have all been considered. The results of these studies reveal a strong relationship between fitness and athletic performance, although the parameters that show the relationship differ depending on the type of test conducted and the athlete's specialty.

In general, data on people's physiques and physical fitness have been widely published, and changes in physical fitness over time, as well as standard values, are well known. However, when it comes to physical fitness data for athletes, there are few records and reports. The Juntendo University Track and Field Club is the team with the most wins in the All Japan Intercollegiate Track and Field Championships, and since 1969, Juntendo University has been conducting cross-sectional and longitudinal research on the physique, physical strength, and athletic ability of students who are continuously engaged in physical training, while conducting cumulative measurements for the purpose of accumulating data (Kohmura and Suzuki, 2018). It is rare to find physical fitness data of university students with a focus on physical education and sports, aggregated by grade and club activity, that have been collected continuously for more than 50 years. This makes the collection being done by Juntendo University a rare one.

With respect to Japanese university track and field events, ekiden and intercollegiate championships are among the most important events. The Hakone Ekiden, which is held at the beginning of the year, is particularly popular, and 10 school representatives compete in 10 sections—5 sections each in the outward (107.5km) and return (109.6km) trips. To demonstrate the best performance on the tracks and aim for overall victory, it is considered important that the top-ranking players in each event, who are the source of points, achieve good results. It is also believed that increasing the physical strength of the entire team will raise the level of competitiveness and build a foundation for aiming for victory. Hence, although track and field is an individual sport, it is also meaningful to conduct various studies from the perspective of the physical strength of athletes who belong to a team.

Therefore, in this study, using the physical fitness data of students belonging to university track and field clubs, we compared the physical fitness data of men of the same age in the general population, clarified their characteristics, and focused on ekiden. The purpose was to examine the relationship between physical fitness parameters and athletic performance. This study is expected to provide data on changes in physical strength of college track and field athletes and basic information on their characteristics, as well as clarify the relationship between physical strength and performance in major college track and field competitions. The knowledge thus acquired will be useful for evaluating the selection of players, devising daily training regimen, and considering tactics and strategies for games. In addition, since data on changes in the physical strength of university track and field athletes over time will be handled, the data can be widely used as reference materials for research in the future.

METHODS

Subjects

We used physical fitness data that were obtained from 1999 to 2019 from male students who belonged to track and field clubs. These data were collected in cumulative measurements at Juntendo University, including statistical data that had already been compiled and published (Committee for Cumulative Records on Physical Fitness, 2000~2019).

The data are the average values for each of the four grades, and the following parameters were measured continuously for 21 years: height, weight, chest circumference, skinfold thickness (of the upper arm and scapula), grip strength, vertical jump, sidestep, and sit and reach test. Along with that, from the statistical data of the physical strength of non-athletic men aged 20 to 24 years, which were compiled by the government (e-Start), common parameters (height, weight, grip strength, sidestep, and sit and reach test), ranking of Hakone Ekiden (Hakone Ekiden official website). The scores for each block in each year's All Japan Intercollegiate Championships were extracted for analysis for the same year (Juntendo University track and field official website). In the All Japan Intercollegiate Championships, points are given according to the grades for each event, and the total score determines the overall grades of each school. In each category, 8 points are awarded for 1st place, 7 points for 2nd place, and so on, down to 1 point for 8th place. Years that were not ranked due to some factors were excluded from the data analysed. This research was conducted with the approval of the research ethics committee of the affiliated institution (approval number 2020-54).

Measurement of skinfold thickness and physical strength

Skinfold thickness

The subject takes a standing posture, and the examiner pinches the subject's skin. He double-pinches the skin deep enough to include the underlying fat but not the underlying muscle. A part 2 cm from the fingertip is measured with a meter. Measurements are taken on the right side only and recorded in mm. Two parts are measured in this way. The skinfold of the extensor surface of the upper arm over the triceps brachii, along the long axis of the arm, is pinched at the point that bisects the distance between the acromion and olecranon.

In the scapular region, the skinfold is pinched laterally, 45 degrees below the midline plane of the body at the point just below the inferior angle of the right scapula.

Grip strength

The dynamometer is held so that its pointers are facing outward. The subject stands upright, opens the legs naturally to the left and right, naturally lowers the arms, and grips the dynamometer as tightly as possible without touching his body or clothes. The measurement is repeated twice for the right and left arms alternately. The average of the best left and right records is calculated.

Vertical jump

Since the measurement method for vertical jump has changed after 2006, the methods used up until 2006 and from 2007 are explained.

Measurement method until 2006: Chalk is placed on the subject's fingertips, and he lies sideways against the wall, standing with the inner leg in contact with the line indicated by the measuring instrument and the outer leg in contact with a line 20 cm away. The hand is extended on the side of the wall as high as possible, and the zero point position of the measuring instrument is set on the tip of the middle finger. Both feet are placed outside the line 20 cm apart, and the subject jumps up as high as possible on the spot, touching the measuring instrument at the highest point.

Measurement method from 2007: A string is fixed to the measurement belt and mat. The subject stands on the mat, and the string is adjusted so that it is not loose. The height of the waist in the standing posture before jumping becomes the standard 0 cm, and the subject jumps as high as possible on the spot.

The measurements obtained with both methods are recorded in cm, and the record is taken for the one that can be performed twice.

Sidestep

A central line is drawn, and two parallel lines are drawn 100 cm on each side of the central line. The subject stands astride the central line and at the start signal, he side steps until he crosses or touches the right line, then returns to the central line and side steps until he crosses or touches the left line. This exercise is repeated for 20 seconds, and 1 point is awarded for each line crossed. The test is done twice, and the better measurement is recorded.

Sit and reach test

The subject takes a long-seated position and puts the back and buttocks against the wall. The centre of the palm is placed on the front edge of the long-sitting flexor, and the gauge is pulled forward with both hands while extending the elbows to straighten the back. Without letting go of the gauge, the subject slowly bends forward and slides the entire gauge straight ahead as far as possible. The hand is released after bending forward to the maximum. The movement distance is measured from the initial posture to the point of maximum forward bending. The movement that can be performed twice is recorded in cm.

For grip strength, sidestep, and sit and reach test, detailed precautions were taken in accordance with the Juntendo University physical fitness cumulative measurement method (Project Committee for Cumulative Records on Physique and Physical Fitness, 1997; Committee for Cumulative Records on Physical Fitness, 2000).

Statistical analysis

Yearly changes in physical fitness data for each block (sprint/hurdle, medium- or long-distance race, jumping, and throwing) and general men's physical fitness data were compared. The results of ekiden were compared with the middle- and long-distance race data, referring to the rankings. In addition, we examined the relationship between each block score in the All Japan Intercollegiate record and each physical strength parameter.

For statistical analysis, Pearson's product-moment correlation coefficient was calculated to verify the relationship between ekiden results, intercollegiate scores, and physical fitness data. The level of significance was set at less than 5%.

RESULTS

Secular trends in the physical fitness data

Figures 1–9 show the secular trends in physical fitness data, classified by event, for students belonging to university track and field clubs. Figures 1, 2, 6, 8, and 9 also show government statistics for men in the general population in Japan.

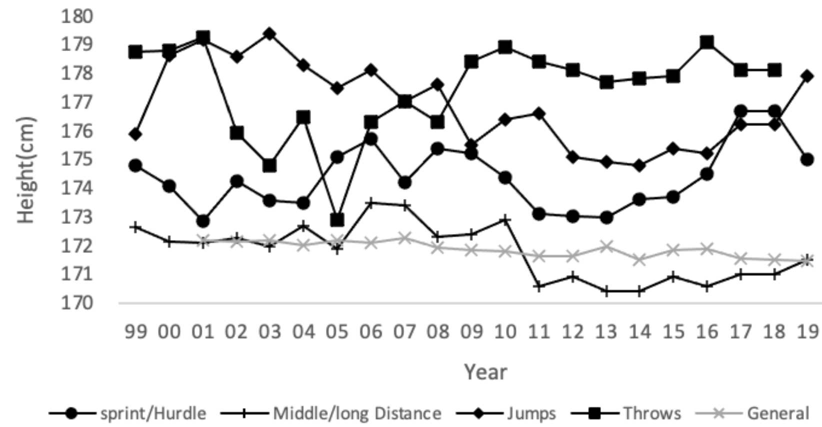

Figure 1. Secular trends in height.

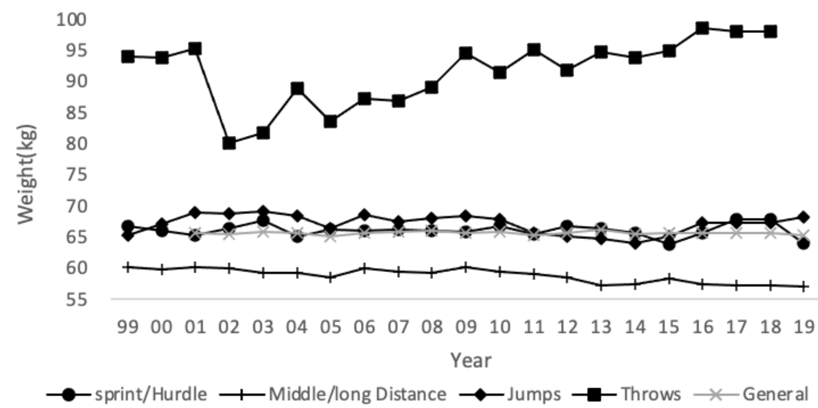

Figure 2. Secular trends in weight.

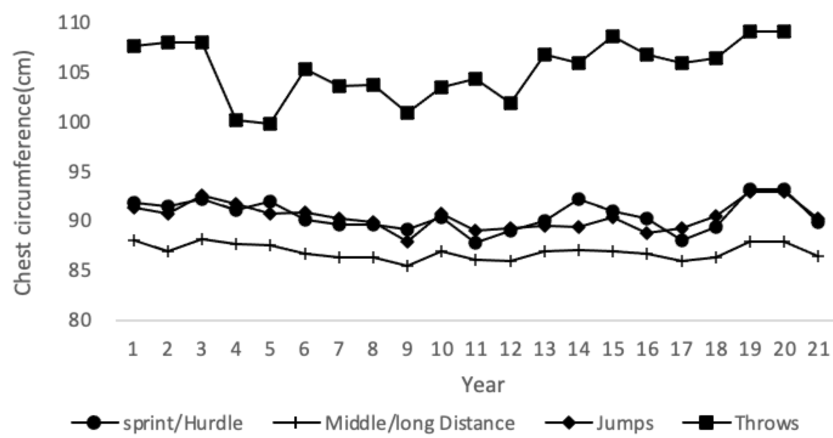

Figure 3. Secular trends in chest circumference.

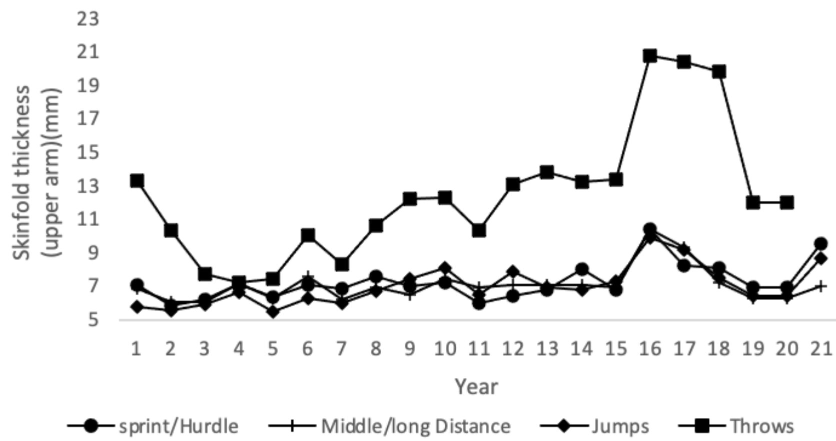

Figure 4. Secular trends in skinfold thickness (upper arm).

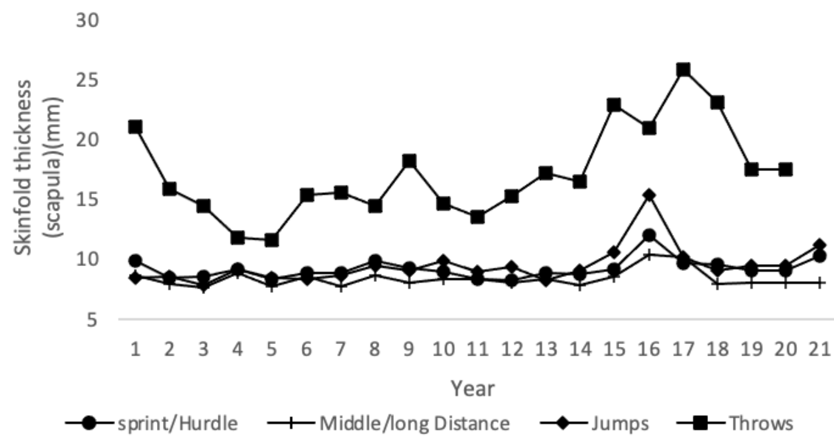

Figure 5. Secular trends in skinfold thickness (scapula).

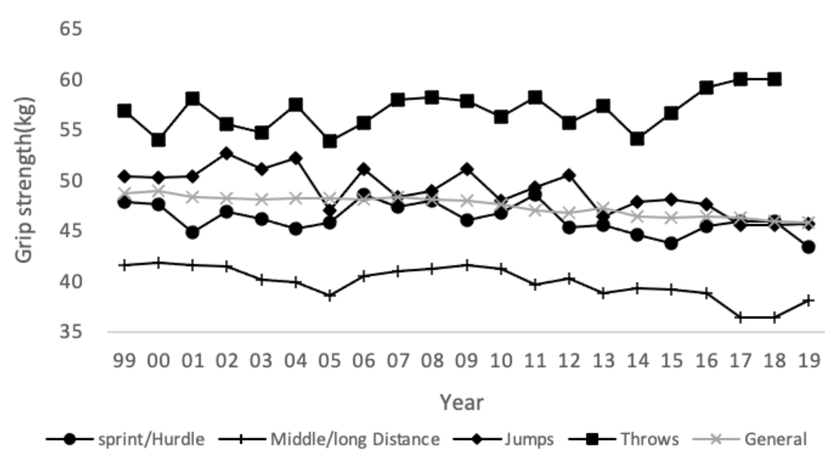

Figure 6. Secular trends in grip strength.

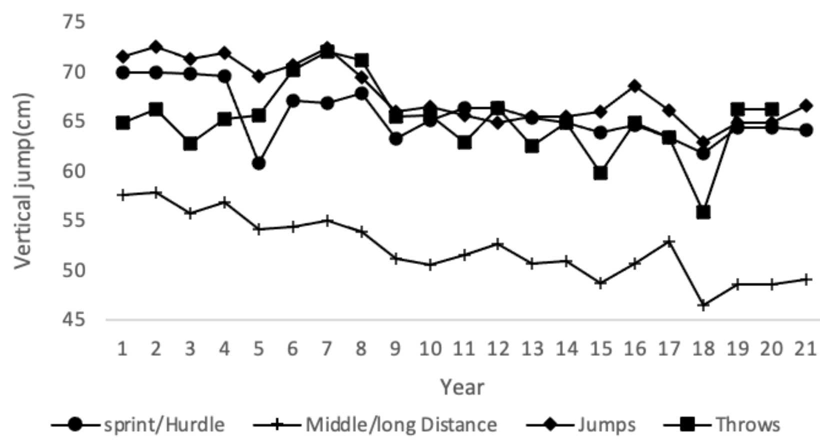

Figure 7. Secular trends in vertical jump.

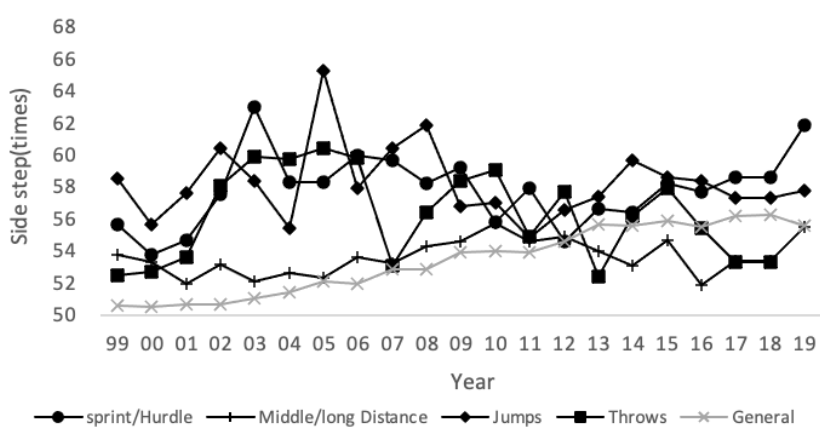

Figure 8. Secular trends inside step.

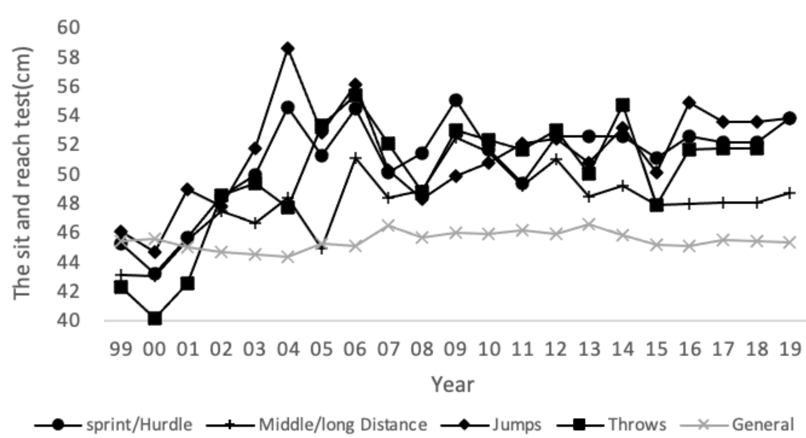

Figure 9. Secular trends in the sit and reach test.

Athletes who specialized in sprinting/hurdles, jumping, and throwing events maintained high values for height. Athletes who specialized in throwing events also had high values for body weight, chest circumference, and skinfold thickness (back of the upper arm and scapula).

Grip strength remained high for athletes who specialized in throwing events, while it remained low for athletes who specialized in medium- and long-distance races. There was a tendency for side-step records to improve over time for men in the general population, but for students of university track and field clubs, the records remained the same. Regarding the vertical jump, the records of university track and field club students tended to decline over time in all events, and the performance of athletes who specialized in middle- and long-distance events remained low. On the other hand, the sit and reach test improved over time in all events, and it remained higher among athletes than among males in the general population.

Relationship between physical fitness data, ekiden results, and all Japan intercollegiate points

Table 1 shows the ekiden rankings and intercollegiate scores for each year. In addition, Table 2 shows the correlation coefficients between the physical fitness data, ekiden ranking, and intercollegiate score.

Table 1. List of intercollegiate points and Ekiden ranking earned by event by year.

	99	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Sprint/Hurdles	26	26	31	6	24	11	53	41	12	21	43
Middle/Long Distance	40	51	44	13	16	26	20	35	46	27	33
Jumps	22	21	16	32	11	14	13	20	10	18	22
Throws	25	11	16	15	13	18	13	24	8	4	17
Ekiden	*1*	*2*	*1*	*2*	*8*	*5*	*5*	*4*	*1*	*DNF*1*	*19*
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	
Sprint/Hurdles	51	15	6	3	3	32	16	9	33	26	
Middle/Long Distance	12	14	7	1	14	19	20	27	20	9	
Jumps	19	12	26	34	34	3	29	24	17	15	
Throws	7	9	15	10	13	7	5	0	0	0	
Ekiden	*DNS*2*	*DNS*2*	*7*	*6*	*16*	*12*	*6*	*4*	*11*	*8*	

*Note. DNF*1: Do not finish. DNS*2: Do not start.*

Table 2. Correlation coefficients between physical fitness data, intercollegiate points, and Ekiden rankings earned by event (r).

	Sprint/Hurdles	**Middle/Long distance**	**Jumps**	**Throws**	**Ekiden**
Height	−0.36	−0.60*	−0.37	−0.15	−0.42
Weight	−0.05	−0.59*	−0.24	−0.36	−0.33
Chest circumference	−0.35	−0.05	−0.14	−0.18	−0.30
Skinfold thickness(upper arm)	−0.34	−0.33	−0.08	−0.30	−0.55*
Skinfold thickness(scapula)	−0.33	−0.20	−0.40	−0.24	−0.46
Grip strength	−0.09	−0.44*	−0.00	−0.49*	−0.25
Vertical jump	−0.23	−0.47*	−0.04	−0.30	−0.42
Sidestep	−0.12	−0.34	−0.04	−0.31	−0.36
The sit and reach test	−0.01	−0.42	−0.06	−0.19	−0.58*

*Note. *: $p < .05$.*

Relationship between ekiden results and physical fitness
Among medium- and long-distance runners, moderate negative correlation was observed between skinfold thickness (upper arm back, r = -0.54) and sit and reach test (r = -0.58), and ekiden results (p < .05).

Relationship between All Japan Intercollegiate points and physical strength
For middle- and long-distance runners, significant moderate positive correlation (r = 0.60, r = 0.59, r = 0.44, and r = 0.47, respectively) was observed between height, weight, grip strength, and vertical jump and scores.

Among throwers, significant moderate negative correlation (r = -0.49) was observed between grip strength and points scored.

DISCUSSION

This study analysed secular trends in the physical fitness data of athletic men in a Japanese university, comparing them with men of the same age in the general population, and explored the relationship between physical fitness and athletic performance.

Transition and comparison of physical fitness data of male students belonging to track and field clubs and men in the general population
Previous studies have suggested that athletes involved in long-distance races have smaller body weight, while those involved in throwing events weigh more (Tanaka et al., 1977). It has also been shown that athletes involved in throwing events tend to have higher fat mass and body fat percentage than those involved in other events (Hirsch et al., 2016). The results of this study are similar to these previous reports. The values of skinfold thickness were similar for athletes involved in all events except throwing events. Studies on skinfold thickness have shown that lower extremity skinfold mass is a useful predictor of running performance in several events such as 400 m, 1,500 m, and 10,000 m races (Legaz and Eston, 2005). It has been argued that skinfold thickness values do not differ among athletes who specialize in distances up to 10,000 m (Arrese et al., 2005). Based on the results of this study, it is possible that there is no difference in the skinfold thickness in the upper extremities among athletes who compete in various events, as in the case of the skinfold thickness in the lower extremities.

With respect to physical fitness parameters, grip strength, which is an evaluation index of muscle strength, the values were similar for athletes who participated in sprints/hurdles and jumping, and they showed a gradual downward trend. In addition, compared to the other three groups, athletes involved in throwing events had high grip strength values, while the medium- and long-distance runners had low values. The vertical jump, which is an evaluation index of muscle power, declined over time in all events, and it remained low in the middle- and long-distance races. The sit and reach test, which is an evaluation index of flexibility, tended to improve over time in all events although its value remained low among medium- and long-distance runners. Previous studies have shown that long-distance runners have lower muscle flexibility in the posterior lower extremities (Wang et al., 1993). The present results may thus provide longitudinal data that support previous reports. Improving flexibility is regarded as an important method of preventing injury, and in recent years, in the field of sports, guidance such as stretching methods and physical care have been actively adopted, spread, and developed by experts and trainers. The flexibility of athletes who have been trained in such settings, regardless of the sport, is higher than that of the general public, and there is a tendency to improve flexibility with such targeted training.

In a long-standing study on physique and body type (Tanaka et al., 1977), the heights of long-distance runners were smaller than the average height of students in the general population, while athletes involved in jumping and throwing events were significantly taller. The results of this study showed a similar trend. Regarding sidestep, which is an evaluation index of agility, there was a trend of improvement among males in the general population, while it levelled off among athletes in all events. From the above, it was clarified that physical strength does not necessarily improve even among college track and field athletes with sufficient exercise habits and intensity.

Relationship between competition results and physical fitness

A significant negative correlation was observed between skinfold thickness on the extensor surface of the upper arm and competition results in ekiden, in which athletes are middle- and long-distance runners with extremely low body fat mass. It has been reported that reduction in skinfold thickness in the lower extremities greatly improved running performance (Legaz and Eston, 2005). On the other hand, there are few useful reports on the relationship between skinfold thickness of the upper extremities and athletic performance. There are also results showing that both lower- and upper-extremity skinfold thickness are not related to performance (Arrese and Ostáriz, 2006). Therefore, the results of this study are contrary to those suggested previously but given the current limited number of reports on skinfold thickness in the upper extremities, it is necessary to further accumulate knowledge on this subject.

The knee joint is frequently injured regardless of running distance (Tschopp and Brunner, 2017), and it has been reported to be significantly associated with hamstring flexibility (Martinez-Cano et al., 2021). In this study, we found a moderate negative correlation between the sit and reach test, which is a popular index for evaluating hamstring flexibility (Mayorga-Vega et al., 2014), and ekiden results. This interesting finding suggests that the flexibility of the posterior leg (mainly the hamstrings) is related to the performance of athletes in the university ekiden. Considering the possibility of hamstring injury, it seems necessary to consider this relationship more carefully.

A relationship was found between grip strength and vertical jump, which are indices of muscle strength and muscle power, and scores obtained in middle- and long-distance races. Maximum oxygen uptake and economy of running are major factors that determine medium- and long-distance running performance (di Prampeco et al., 1986; Stratton et al., 2009). Intense strength training can improve running performance and maximal running speed (Skovgaard et al., 2014; Mikkola et al., 2011). Furthermore, anaerobic capacity and neuromuscular performance are enhanced, which can be expected to improve sprinting ability and economy of running in the second half of the race (Taipale et al., 2010; Jung, 2003; Blagrove et al., 2018). Based on the above, the results of this study with respect to middle- and long-distance running performance may also be related to competition results. In addition, there was a correlation between height and weight, and points scored for middle- and long-distance races, but among middle-distance and 3,000 m steeplechase runners, there was a correlation of points scored with the athletes' morphological size, which also affects the exertion of muscle strength and explosive power. A negative correlation was also observed between the performance of throwers and grip strength. Throwers require a certain level of muscle strength, but beyond that, it is conceivable that other factors such as technique are involved in competitive performance.

However, in this study, since verification was based on statistical data using the average value of each group, it is difficult to rigorously consider and interpret the relationships of the parameters with the intercollegiate results of several contestants. This is a limitation of our study, and further investigation is required in the future.

CONCLUSION

In this study, we examined the relationship between the annual changes in the physical fitness of male students belonging to a university's track and field clubs, results of ekiden, and intercollegiate scores. The main findings are as follows:

1. There was no difference in the skinfold thickness of the upper extremity among athletes involved in various events, except for the throwing events.
2. Grip strength declined gradually among athletes involved in sprints, hurdles, and jumping events, with values similar to those obtained among males in the general population. Throwers however had high grip strength. Vertical jump records tended to decline over time among all kinds of athletes, and they remained at low levels among middle- and long-distance runners. Regarding the repeated sidestep, while males in the general population tended to improve, the performance of athletes tended to remain the same.
3. Flexibility of the lower extremities (mainly hamstrings) has been shown to be related to athletic performance in university relay races, but considering the possibility of accompanying disability, it is necessary to carefully examine it in the future.
4. A relationship was found between grip strength and vertical jump, which are indices of muscle strength and muscle power, and scores obtained in middle- and long-distance races. These parameters may contribute to the achievement of excellent athletic results in college track and field athletes who specialize in middle- and long-distance races.

AUTHOR CONTRIBUTIONS

The concept for this study was proposed by Matsumoto and Kohmura. Matsumoto collected and analysed the data and prepared the first draft. Kohmura, Nakamura, Takanashi and Aoki contributed to data analyses, results interpretation, and final draft writing process.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

We would like to thank Editage (www.editage.com) for English language editing.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

The effect of acute caffeine ingestion on physical performance in elite European competitive soccer match-play

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ABSTRACT

The present study examined the effect of acute caffeine ingestion (150 mg) on the physical performance of elite European soccer players during official competitive match-play. The current investigation was a parallel-group design that collated data from a cohort of 19 male outfield players from an elite European soccer team (mean ± SD, age 26 ± 4 years; weight 80.5 ± 8.1 kg; height 1.83 ± 0.07 m; body-fat 10.8 ± 0.7%). Players were classified and matched by position and grouped accordingly: centre defender (CD) n = 5, wide defender (WD) n = 3, centre midfield (CM) n = 7, wide forward (WF) n = 2, and centre forward (CF) n = 2. For all performance variables, the mean values were compared in caffeine consumers vs. non consumers using independent-sample t-tests, with significance set at $p < .05$. Cohen's d was used to quantify the effect size, and was interpreted as trivial (<0.2), small (0.2-0.5), medium (0.5-0.8), and large (>0.8). For all examined variables, there were trivial or small non-significant ($p > .05$) trivial or small differences between caffeine consumers and non-consumers. The findings of the present research did not confirm the study hypothesis, once running and accelerometry-based variables did not improve with the caffeine ingestion of 150 mg. Therefore, the caffeine supplement used in this study is not suggested for improving performance in the variables analysed.
Keywords: Performance analysis, Physical conditioning, Football, Soccer, Caffeine, Match performance, Supplementation.

Cite this article as:
Morgans, R., Rhodes, D., Orme, P., Bezuglov, E., Di Michele, R., Teixeira, J., & Oliveira, R. (2023). The effect of acute caffeine ingestion on physical performance in elite European competitive soccer match-play. *Scientific Journal of Sport and Performance*, 2(3), 402-409. https://doi.org/10.55860/BDXS3572

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Submitted for publication June 04, 2023.
Accepted for publication June 13, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/BDXS3572

INTRODUCTION

Caffeine is a commercially available drug that is widely used by athletes across many sports around the world. Previous research has shown that high numbers of athletes consume some form of caffeine around competition (Del Coso et al., 2012). The potential benefits of caffeine supplementation have previously been documented (Del Coso et al., 2012; Burke, 2008; Mielgo-Ayuso et al., 2019; Stadheim et al., 2021; Tallis et al., 2021). Although, some of these studies have tended to be laboratory-based investigations with less understanding of the effects of caffeine on physical and physiological performance in "*real-world*" settings.

From the perspective of performance enhancement for soccer match-play, the consumption of caffeine may have various advantages. These include the enhancement of oxygen utilisation, increased carbohydrate utilisation, improved power performance, enhanced cognitive function, and increased time to fatigue (Hogervorst et al., 2008; Mielgo-Ayuso et al., 2019; Stadheim et al., 2021). However, it is important to note that the required dosage and timing of ingestion to attain these performance enhancements may vary between individuals (Burke, 2008). It is also important to consider the potential detrimental effects of consuming high amounts of caffeine. In particular, in soccer, many matches across the season are played late in the evening, where caffeine ingestion may affect players ability to sleep following the match, which may in turn be unfavourable for the recovery processes that need to occur before resuming training for the subsequent match (Drake et al., 2013; Nedelec et al., 2015). Furthermore, some individuals may be more sensitive to caffeine which may cause anxiety, nausea or migraine onset (Tallis et al., 2021).

The use of caffeine supplementation in soccer is prevalent through various methods of ingestion including sports/energy drinks, tablets, chewing gum, gels, and specially formulated "*caffeine shot drinks*" (Mielgo-Ayuso et al., 2019). Previous research has attempted to better understand the effects of caffeine supplementation on soccer performance using simulated soccer match-play (Del Coso et al., 2012). The authors assessed the effects of ingesting 3mg of caffeine per kilogram of body mass versus a decaffeinated control drink on repeated sprint ability, maximal jump and physical performance during the simulated soccer match. An improvement in repeated sprint ability and an increase in distance covered at high intensity during the simulated match was reported. Further to this, Ellis et al. (2019) found that smaller doses of caffeine (1-3 mg/kg) may also be beneficial to the performance characteristics of elite adolescent male soccer players during a series of physical tests.

There seems to be a lack of empirical evidence highlighting the effects of caffeine supplementation on physical performance during actual "*real-world*" elite soccer match-play. Furthermore, it would appear that more research is warranted to fully understand the optimal dosage and timing required to elicit performance benefits from caffeine supplementation in official competitive soccer match-play. To address this gap in the literature, the present study examined the effect of acute caffeine ingestion (150 mg) on the physical performance of elite European soccer players during official competitive match-play. It was hypothesised that acute caffeine ingestion would improve physical performance in elite soccer match-play.

METHOD

Participants and study design

This study examined 19 male soccer players over a full season in an elite European league. The participants had been playing soccer for a minimum of 10 years. During a regular week and study period, players were instructed to maintain normal daily food and water intake, and no additional dietary interventions were undertaken. Specific caffeine ingestion was restricted to 45-minutes prior to kick-off on match-day.

The current investigation was a parallel-group design that collated data from a cohort of 19 male outfield players from an elite European soccer team (mean ± SD, age 26 ± 4 years; weight 80.5 ± 8.1 kg; height 1.83 ± 0.07 m; body-fat 10.8 ± 0.7%). Players were classified and matched by position and grouped accordingly: center defender (CD) n = 5, wide defender (WD) n = 3, center midfield (CM) n = 7, wide forward (WF) n = 2, and center forward (CF) n = 2. Goal-keepers were excluded from the investigation due to the specific nature of their match activity and their low running demands (Ingebrigtsen et al., 2015; Bradley et al., 2009). The sample were initially recruited based on squad selection across 30 league matches (home matches n = 15, away matches n = 15) in the 2021-22 season. Only data recorded during home and away official league matches were included in the present study. The sample was further sub-divided into caffeine users (n = 9) and non-caffeine users (n = 10). Data were only included in the analyses as starting player when the participant was selected in the starting line-up and match playing time exceeded 30-minutes of the match and they completed three (10%) or more league matches. Participants competed in a median of 43% (range = 10 to 93%) of league matches during this phase. All data evolved as a result of employment in which players were routinely monitored over the course of the competitive season. Nevertheless, approval for the study from the club was obtained (Winter and Maughan, 2009) and all participants provided written informed consent. The study was performed in accordance with the Helsinki Declaration principles and ethical approval was granted by the local Ethics Committee of Sechenov University (N 22-21 dated 12/12/2021). To ensure confidentiality, all data were anonymised before analysis. Participants were fully familiarised with the experimental procedures within this study due to regular protocols implemented as part of the clubs' performance monitoring strategy.

Design and procedures

The study period involved all match performance across the 2021-2022 season. The training sessions performed during the investigation were representative of a typical training micro-cycle implemented within elite soccer, involving a periodised training week encompassing low-, moderate-, and high-intensity sessions leading to competitive match-play.

All participants performed several familiarisation sessions one week prior to the first experimental session (first league match). The participants ingested a commercially available caffeine supplement (150 mg caffeine and 2 g L-Citrulline DL Malate; SIS®, London, UK) of 60 mL of cold cola flavoured solution or a flavoured solution alone, which was used as a placebo. Solutions were considered identical in flavour and colour by two researchers involved in the study. Participants were asked to follow their normal match-day diet and pre-match routines and abstain from caffeine consumption (in drinks and supplements) 24-hours prior to experimental sessions (match-play). All experimental sessions commenced in the afternoon or evening (12:30 to 19:00) with an interval of 6-7 days between matches. Fifteen minutes following the consumption of caffeine or placebo solutions, participants performed a generic individual warm-up consisting of body-weight exercises and dynamic stretching of relevant lower limb musculature, followed by a specific pitch-based team warm up protocol consisting of additional dynamic movements, running at various speeds over different distances and football specific practices (passing, small-sided games and positional activities) where hydration was *ad libitum*. The complete warm up protocol consisted of 22-minutes of activity.

Data collection

League match performance data were collected using a two-camera optical tracking system (InStat, Moscow, Russia) that was installed to record and examine the technical and physical match performance during competitive league fixtures. The matches were filmed using two full HD, static cameras positioned on the centre line of the field, not less than 3-metres from the field and 7-metres in height. A consistent 25 Hz format was provided. Data were linearly interpolated to 50 Hz, smoothed using a 5-point moving average and then down-sampled to 10 Hz, which allowed analysis of all player actions with and without the ball. The installation process, reliability, and validity of InStat have been previously reported (FIFA, 2019). Technical and physical performance was analysed using the InStat Analysis Software System and exported to the Microsoft Excel software for further analyses. InStat provided written permission to allow all match data to be used for research purposes.

The physical match activity profile included: total distance covered (m/min); high-intensity distance (m/min; total distance covered 5.5 - 7m/s); sprint distance (m/min; total distance covered >7m/s); acceleration distance (m/min distance covered during accelerations +3m/s^{-2}); deceleration distance (m/min; distance covered during decelerations +3m/s^{-2}). For all variables, the mean individual seasonal value was calculated for each player and used for subsequent analyses.

Statistical analysis

All data are presented as the mean ± standard deviation (SD). For all performance variables, the mean values were compared in caffeine consumers vs. non consumers using independent-sample t-tests, with significance set at $p < .05$. Cohen's d was used to quantify the effect size, and was interpreted as trivial (<0.2), small (0.2-0.5), medium (0.5-0.8), and large (>0.8). The analysis was conducted using the software R, version 4.2.0.

RESULTS

Table 1 shows the mean values for the examined distance metrics in players having consumed or not consumed caffeine before match play. For all examined variables, there were trivial or small non-significant ($p > .05$) trivial or small differences between caffeine consumers and non-consumers.

Table 1. Comparisons of match physical performance variables in caffeine between consumers and non-consumers.

Variable	Caffeine consumers	Caffeine non consumers	*p*-value	Cohens' d
Total distance (m/min)	116.0 ± 8.9	118.4 ± 8.6	.62	0.24
High-intensity distance (m/min)	8.49 ± 2.49	8.60 ± 1.79	.91	0.05
Sprint distance (m/min)	1.15 ± 0.30	1.46 ± 0.76	.30	0.49
Acceleration distance (m/min)	1.63 ± 0.31	1.63 ± 0.31	.98	0.01
Deceleration distance (m/min)	0.58 ± 0.15	0.58 ± 0.10	1.00	0.00

DISCUSSION

The aim of this study was to analyse the effects of acute caffeine ingestion on the physical performance of elite European soccer players during official competitive match-play. The main findings showed no differences between groups which could be related to the fact that only 150 mg were administered by the caffeine consumers group. Considering the average weight of the participants, this represents approximately 1.8 mg/kg. This finding is in line with previous studies (Burke et al., 2008; Coso et al., 2012) that only found significant improvements in performance with higher dosages (>3 mg/kg). In fact, the lower dosages (<2 mg/kg) were not included in a systematic review on the effects of acute caffeine ingestion on team sports performance based on previous studies showing no effects of such low caffeine (Burke et al., 2008; Del Coso et al., 2012; Astorino et al., 2010; Del Coso et al., 2012; Turley et al., 2015). Even so, there are contrasting research that suggests that lower doses (<3 mg/kg) can be beneficial for psychological and physical performance in similar magnitudes, although this may vary across individuals (Spriet, 2014).

The rationale of the present research was based on studies that supported a positive effect on performance with lower dosages of caffeine (Ellis et al., 2019; Ranchordas et al., 2018). For instance, a recent study found positive performance results with 1 – 2 mg/kg in U-17 youth soccer player (Ellis et al., 2019). Specifically, the change of direction tests of both legs, peak power, mean power, and peak velocity improved with a 2 mg/kg caffeine dose compared to a placebo. Additionally, 1mg/kg of caffeine improved peak force in the control group when compared to the placebo group. Jump ability and aerobic capacity were also improved with 1 – 2 mg/kg of caffeine. Meanwhile, Ranchordas et al. (2018) analysed whether caffeinated gum (200 mg) influenced performance in a battery of soccer-specific tests in male university soccer players (U-20). The authors found that Yo-Yo Intermittent Recovery Test Level 1 distance and countermovement jump were improved by the chewing of caffeinated gum. However, these studies had significantly younger participants than those of the present research which may be an interesting variable to consider in future research (i.e., performing comparisons for different age groups).

Moreover, it is relevant to acknowledge that only two studies were found to analyse running and accelerometry-based variables in match activity in U-18 soccer players, using a higher dosage of 6 mg/kg (Pettersen et al., 2014) and in semi-professional soccer players using a 3 mg/kg dose of caffeine (Del Coso et al., 2012). On the one hand, Pettersen et al. (2014) found no significant effects while Del Coso et al. (2012) found that total distance covered at a speed higher than 13 km/h was improved. The distinct participants, methodologies (including caffeine dosages) and result suggest that more research is warranted.

It seems that this was the first study that analysed professional soccer players from the same team with a limited number of participants. Finally, the non-existence of a pre- versus post-comparison could also strengthen the results and should be considered in future studies.

Considering the non-existent research in professional soccer players through official matches with running and accelerometry-based variables, this study suggests more research with professional soccer players with higher dosages of caffeine (i.e., > 3 mg/kg) which may provoke different effects as suggested in previous studies (Burke et al., 2008; Coso et al., 2012) is required.

CONCLUSIONS

The findings of the present research did not confirm the study hypothesis, once running and accelerometry-based variables did not improve with the caffeine ingestion of 150 mg. Therefore, the caffeine supplement used in this study is not suggested for improving performance in the variables analysed.

AUTHOR CONTRIBUTIONS

Conceptualization: Ryland Morgans, Dave Rhodes, Eduard Bezuglov, Jose Teixeira, Toni Modric, Sime Versic and Rafael Oliveira. Methodology: Ryland Morgans. Software: Rocco Di Michele. Validation: Ryland Morgans, Eduard Bezuglov, Rafael Oliveira and Rocco Di Michele. Formal analysis: Rocco Di Michele. Investigation: Ryland Morgans, Dave Rhodes, Patrick Orme, Jose Teixeira, Toni Modric, Sime Versic and Rafael Oliveira. Resources: Ryland Morgans and Eduard Bezuglov. Data curation: Ryland Morgans. Writing—original draft preparation: Ryland Morgans, Patrick Orme, Rocco Di Michele and Rafael Oliveira. Writing—review and editing: Ryland Morgans, Eduard Bezuglov, Dave Rhodes, Jose Teixeira, Toni Modric, Sime Versic, Rocco Di Michele and Rafael Oliveira. Visualization: Ryland Morgans and Rocco Di Michele. Supervision: Ryland Morgans. Project administration: Ryland Morgans. All authors have read and agreed to the published version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS STATEMENT

The study was performed in accordance with the Helsinki Declaration principles and ethical approval was granted by the local Ethics Committee of Sechenov University (N 22-21 dated 12/12/2021).

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study.

ACKNOWLEDGEMENTS

The authors want to thank all the players, and medical staff involved in the study for the professionalism shown throughout. The authors also want to state that the results of the present study do not constitute endorsement of any products.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

The effects of a single or multi-step drop-set training compared to traditional resistance training on muscle performance and body composition

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ABSTRACT

The purpose was to examine two drop-set (DS) protocols (single step vs. multi-step) compared to traditional resistance training (TRT) over 8 weeks on changes in muscular strength, endurance and body composition. Twenty-seven trained males were randomized to one of three groups: traditional resistance training (TRT: n = 9), the single step drop set group (DS-S: n = 10) and the multi-step drop set group (DS-M: n = 8). Before and after training, body composition (percent body fat and skeletal muscle mass), and muscular strength and endurance (bench and leg press) were determined. Results: There was a significant interaction for leg press 1-RM ($p < .001$) and absolute change for leg-press 1-RM was significantly greater for both drop set protocols compared to TRT ($p < .001$). There were significant interactions for both leg press and bench press endurance ($p < .001$), with post hoc analyses revealing that only DS-M was superior to TRT ($p < .001$). There was a significant main effect of time for % body fat ($p = .020$), SMM ($p < .001$), however there were no differences between groups. Conclusions: Overall, single-step and multi-step drop-set training to failure appear to be effective strategies to enhance lower body strength, while only the multi-step drop set training enhanced muscular endurance compared to TRT.
Keywords: Performance analysis, Physical conditioning, Muscle strength, Muscular failure, Muscle endurance, MVC, Mechanical tension.

Cite this article as:
Fasihiyan, M., Forbes, S., Taheri, M., Gomez Lopez, J., Babaie, M., Dejam, B., & Nourshahi, M. (2023). The effects of a single or multi-step drop-set training compared to traditional resistance training on muscle performance and body composition. *Scientific Journal of Sport and Performance*, *2*(3), 410-422. https://doi.org/10.55860/ZMKL1980

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Submitted for publication June 05, 2023.
Accepted for publication June 13, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/ZMKL1980

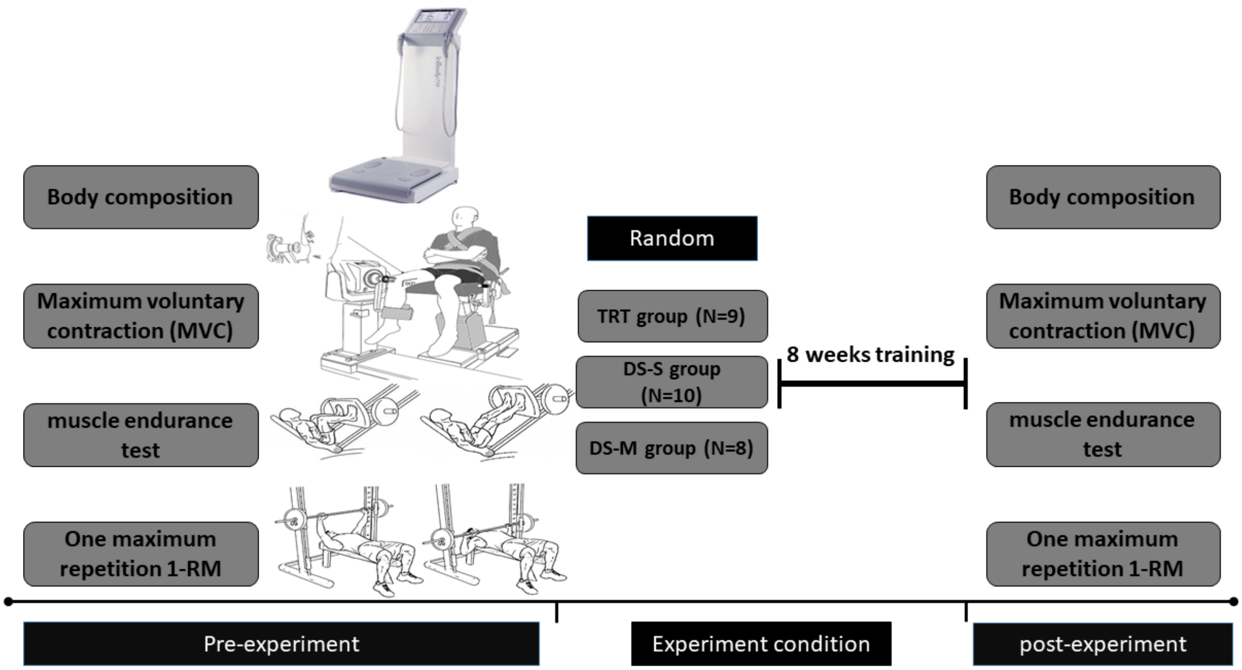
INTRODUCTION

Resistance training is a well-established robust strategy to augment gains in muscular strength and endurance and hypertrophy (Kraemer and Ratamess., 2004). Mechanistically, muscle hypertrophy appears to be associated with mechanical tension, metabolic stress, and cell swelling (Lawson et al., 2022; Wackerhage et al.,2019). Furthermore, resistance training alters structural elements of the muscle, such as the angle of tendon adhesion and length (Pallarés et al., 2021; Seynnes et al., 2007). From an applied perspective, manipulating resistance training programming variables (e.g., sets, repetitions, proximity to failure, volume, frequency, tempo, etc.) may alter the exercise-induced gains in muscle strength and endurance and muscle size (Wilk et al., 2021). Traditional resistance training (TRT) is an effective strategy to induce gains in muscle size and strength, however, alternative strategies, such as drop-sets (DS) have been purported to further enhance these adaptations (Krzysztofik et al., 2019; Angleri et al., 2017). TRT is characterized by multiple sets performed with the same load (i.e., % of 1-RM) with a pre-determined rest interval (Enes et al., 2021; Giessing, et al., 2016). In contrast, DS training involves performing an exercise to (or in close proximity to) momentary failure followed by an immediate reduction in load prior to performing an additional set (Lasevicius et al., 2022; Nuzzo et al., 2023). Depending on the protocol, single or multiple reductions or "*drops*" can be performed. DS training may benefit adaptations through enhanced time under tension, metabolic stress and metabolite accumulation, and cell swelling compared to TRT. Conversely, DS training may impair gains in strength since high load training with longer rest intervals appears to be ideal for optimizing strength gains (Coleman et al., 2022; Schoenfeld et al., 2021). A recent meta-analysis comparing DS to TRT indicated trivial point estimates of the effect sizes for gains in muscle size and strength, however, only 5 studies met the inclusion criteria Furthermore, there were numerous methodological differences between studies, including large variations in DS protocols (Coleman et al., 2022). For example, Angleri et al. and Fink et al., utilized two-step reduction drop-set protocols (20% reduction per step) (Angleri, et al., 2017; Fink et al., 2018), the previous study showed participants had performed 3 sets of 10 repetitions plus one drop set of 6 repetitions (Enes et al., 2021), another study implemented a single drop-set beginning with a high load (80% 1-RM) with 4 descending sets to 30% 1-RM (Ozaki et al., 2018), and also in the other research had participants perform a 5-RM to failure, immediately reducing load by 20%, and then another drop by 10-15% (Varovic et al., 2019). Presently the optimal DS protocol is unknown. Therefore, the purpose of this study was to compare two drop set protocols (single step vs. multi-step) on changes in muscle strength and endurance, and body composition after 8 weeks compared to TRT in resistance trained individuals. In theory, multi-step drop sets would induce greater metabolic disturbances and may result in greater gains in hypertrophy and muscular endurance but may impair muscular strength compared to a single drop set protocol and traditional resistance training.

METHODS

Experimental approach of the problem

A randomized pre-post repeated measure design was used to investigate changes in two DS protocols compared to TRT over 8 weeks. Healthy young resistance trained males were randomized to one of three independent groups: TRT (n = 9) completed 4 sets of 10 repetitions at 75% of 1-RM with 90 seconds rest between sets; the single step drop-set group (DS-S: n = 10) performed two sets beginning at 80% and dropping to 45% of 1-RM until failure with 90 seconds rest between sets; the multi-step drop-set group (DS-M: n = 8) performed a single drop set corresponding to 80, 65, 50, and 35% 1-RM performed until failure. All groups trained 3 times per week for 8 weeks. Before and after training, body composition (percent body fat and skeletal muscle mass), upper and lower body muscular strength (1-RM) and endurance (40% 1-RM to failure), and isometric leg extension strength were determined. Body composition was assessed via a bioelectrical impedance analysis (InBody 770). The experimental design is shown in Figure 1.



Note. TRT = Traditional resistance training, DS-S = Single step drop-set; DS-M = DS with multiple steps.

Figure 1. Experimental design.

Subjects

An a priori power analysis (G-Power v.3.1.5.1) indicated that N = 30 subjects were required (n = 10/group). This calculation was based on an effect size (0.25), an alpha level of .05, and a ß-value of 0.8 for a repeated measures analysis of variance (ANOVA) design with 3 groups and a correlation among repeated measures of 0.5. As such, thirty participants were recruited using the non-probabilistic sampling method.

Table 1. Descriptive data of the subjects, mean ± SD.

Variables	**TRT (N = 9)**	**DS-S (N = 10)**	**DS-M (N = 8)**
Age (years)	27 ± 5	27.6 ± 4.8	25.9 ± 7.1
Body mass (kg)	73 ± 9.3	75.5 ± 7.4	76 ± 6.2
Height (cm)	174 ± 4.5	179 ± 6.6	173 ± 7.5
Body Fat (%)	15.1 ± 2.35	15.5 ± 3.4	14.7 ± 2.1
SMM (Kg)	35.6 ± 3.5	36.2 ± 4.1	36 ± 3.7
MVC (Nm)	271.4 ± 15.8	278 ± 20.5	280.8 ± 24.3
1RM leg press (kg)	263.6 ± 25.3	248.2 ± 31.5	259.8 ± 26.9
1RM bench press (kg)	112 ± 10.7	120 ± 8.5	116 ± 5.9
ME leg press (reps)	43.4 ± 9.2	40.1 ± 7.5	42.7 ± 11.2
ME bench press (reps)	29.8 ± 5.7	32 ± 7.4	31.4 ± 6.6

Note. SMM = Skeletal muscle mass; MVC = Maximum voluntary isometric contraction; 1RM = One-repetition maximum; ME = Muscle endurance; TRT = Traditional resistance training; DS-S = Single step drop-set; DS-M = DS with multiple steps.

Participants were free of any disease including cardiovascular diseases, hypertension, diabetes, or any other chronic disease that would alter muscle biology or impact the safety of the exercise program. Participants were also not taking any medicine or dietary supplements (e.g., creatine) within 6 months before the start of the study. Furthermore, participants had to have at least 6 months of resistance training experience and not currently using drop set training in their programs. Lastly, participants were excluded if they have recently experienced a muscle, joint, or tendon injury that would impact their ability to train, or if they missed two or more training sessions, or were unable to follow the training protocols as prescribed. Prior to the start of the study, all participants were informed of the risks and benefits and signed an approved informed consent document to participate in the study. The study was approved by an Institutional Ethics Review Board at the Shahid Beheshti University of Tehran (IR.SBU.REC.1400.161). Subject characteristics are shown in Table 1.

Procedures

Muscular strength (1-RM) and endurance

For initial assessment a 1-RM test was used to assess upper (bench press) and lower body (leg press) muscular strength. At the start of the assessment a warm-up was performed that consisted of 5 minutes of low intensity walking on a treadmill followed by 8 repetitions with a load that would achieve a 4-6 score on a 1-10 ratings of perceived exertion (RPE) scale. After 1 minute of rest, 3 repetitions were performed with a load corresponding to ~70% of an estimated maximum RPE (7 out of 10). After 3 minutes of rest, participants completed three to five 1-RM attempts with progressively heavier loads (~5% increase following a successful attempt) interspersed with 3–5 minutes of rest until a 1-RM was achieved. Bench press was assessed first, followed by a 5-minute rest before the same protocol was followed for leg press. The range of motion and exercises technique were standardized according to previously described protocols (Recio et al., 2018). The 1-RM tests (test-retest) were conducted on 2 non-consecutive days (minimum of 72 hours between tests). The intraclass correlation coefficient was r = 0.95 for both upper and lower body 1-RM. Once the 1RM was determined, 40% of this value was calculated for the muscular endurance tests. After a standardized recovery period (5 minutes), the subjects performed as many repetitions as possible with 40% of 1RM until failure for both exercises (Recio et al., 2018; Lasevicius et al., 2022; , Schoenfeld et al., 2021). The maximum number of repetitions that were performed correctly without rest or stopping was recorded. All testing sessions were performed at the same time of day.

Resistance training protocols

Prior to each training session a standardized warm-up was completed (Ribeiro et al., 2014). The warm-up consisted of a 5-minute general warm-up that included running or walking on a treadmill and 5 minutes of specialized movements focused on the primary muscles and joints. Following the warm-up, participants trained their upper (bench press) and lower (leg press) body. In the traditional resistance training (TRT) group, participants performed each exercise for 4 sets of 10 repetitions, at an intensity based on their 10-RM or 75% of their 1-RM achieved at baseline. The rest interval between each set was 90 seconds, and the rest between exercises was 3 minutes. In the single-step drop-set (DS-S) group, the participants performed two sets each beginning at 80% of their 1-RM performed until exhaustion followed by a single step drop to 45% of their 1-RM completed to muscle exhaustion with 90 seconds rest between sets and with a 3-minute rest between exercises. In the multi-step drop-set (DS-M) group, the participants started with a load that corresponded to 80% of their 1-RM and continued until muscular exhaustion, then the load was immediately reduced by 15% to 65% of 1-RM, then 50% of 1-RM, and 35% of 1-RM. The load was changed as quickly as possible between step reductions and the rest time between exercises was 3 minutes. All groups completed each repetition at a tempo of 1.1.1.1 (concentric, pause, eccentric, pause). The exercise protocols in all 3 groups are shown in Table 2.

Table 2. Resistance training protocols.

Group	Set	Rep	Load	Rest	*Tempo*
TRT	4	10	75% 1RM	90s	1-1-1-1
DS-S	2	Failure	80% - 45%	90s (between sets)	1-1-1-1
DS-M	1	Failure	80% - 65% - 50% - 35%	-	1-1-1-1

Training volume

The average total training volume (TTV) during the 8 weeks of training was calculated based on (sets × repetitions × load [kg]) for bench press, leg press and for overall total volume (Schoenfeld et al., 2019). The total training volume in bench press, leg press and overall are shown in Table 3.

Table 3. Total training volume, mean ± SD.

Group	Ttv (Kg) Bench Press	Ttv (Kg) Leg Press	Ttv (Kg) Overall
TRT	3480 ± 390	8680 ± 525	12160 ± 915
DS-S	3418 ± 318	8362 ± 463	11780 ± 781
DS-M	3251 ± 384	8160 ± 585	11411 ± 969

Body composition

An InBody 770 multi frequency bioelectrical impedance analysis was used to estimate body fat percentage and skeletal muscle mass. Previous research has shown that multi-frequency bioelectrical impedance analysis (MF-BIA) is a suitable alternative to dual-energy x-ray absorptiometry (DXA) method (Antonio et al., 2019).

Maximum isometric strength

Maximal voluntary isometric contraction (MVC) strength was assessed with a System 4 Pro™ Biodex isokinetic dynamometer to determine the maximum amount of force that could be produced during a leg extension. Participants were seated on the chair of the machine, and the examiner adjusted the machine according to their individual characteristics to ensure proper movement mechanics. After a 5-minute general warm-up on a cycle ergometer, the subjects were asked to perform 10 submaximal isometric repetitions (holding for 3 seconds) at an angle of 75 degrees (relative to the zero angle in full extension). Three minutes later 5 maximum repetitions were performed interspersed with 15-second rest intervals between each attempt. The highest peak torque was considered the highest isometric voluntary contraction for each subject (Tittelboom et al., 2022).

Dietary intake

All participants completed a 3-day dietary record before the intervention and then at the mid-point and conclusion of the study. Total energy and macronutrient intake were calculated. Dietary intake was broken down into specific amounts of macronutrients (carbohydrate, protein, and fat) which included the total percentage of each macronutrient, the number of calories, and the amount consumed in grams, also the total number of daily calories was calculated. To enhance the accuracy of data, a certified nutritionist assisted participants to estimate their food and drink portions (Boidin et al., 2021). All participants were encouraged to maintain their habitual dietary intake throughout the entire study. No significant between-group differences were observed for the average total daily calories and macronutrients (Table 4).

Table 4. Average total daily calories and macronutrients, mean ± SD.

Variables	TRT	DS-S	DS-M
Total daily Kcal (Kcal)	2290 ± 251.9	2398 ± 215.8	2365 ± 260.1
Total CHO (%)	57 ± 6	58 ± 3	56 ± 5
CHO/kg (g/kg)	4.3	4.7	4.4
Total PRO (%)	18 ± 3	17 ± 2	17 ± 3
PRO/kg (g/kg)	1.35	1.32	1.35
Total FAT (%)	26 ± 2	25 ± 4	27 ± 3
FAT/kg	0.9	0.88	0.91

Note. CHO = Carbohydrate; PRO = Protein; Kcal = Kilocalorie.

Statistical analyses

The primary analysis performed was a 3 (group: TRT vs. DS-S vs. DS-M) by 2 (time: pre-training vs. post training) repeated measures ANOVA to determine differences between groups over time for changes in body composition (% body fat, SMM) and muscle performance measures. If a significant effect was found, a Tukey's pairwise post-hoc comparison was completed. Significance was set at $p \leq .05$. The magnitude of the difference between significant means was determined by partial eta squared (η^2). This is a measure of the effect size and therefore of the proportion of the total variance that can be explained by the effects of the treatment. A η^2 value of 0.15 represents large differences, 0.06 represents medium differences, and 0.01 represents small differences. A one-factor ANOVA was used to assess baseline data, training volume, and absolute change scores (post values minus pre values). All statistical analyses were performed using the Statistica v. 13.3 (StataCorp LLC, College Station, TX, USA).

RESULTS

Three subjects were excluded due low adherence and lack of availability to the exercise program. Therefore, only twenty-seven participants completed the training and were included in the analysis. Of these 27 participants, they all had high adherence (>95%) to the exercise program. There were no significant ($p > .05$) differences between groups for any participant characteristics or outcome variables at baseline, as shown in Table 1. Furthermore, there were no significant differences between groups for carbohydrates, protein, fat, or total caloric intake ($p > .05$), as shown in Table 4.

Body composition

There was no significant interaction ($p = .729$) for % body fat, however there was a significant main effect of time ($p = .020$; $\eta^2 = 0.206$; TRT: 15.1 ± 2.4 to 14.9 ± 2.1%; DS-S: 15.5 ± 3.4 to 15.3 ± 3.2%; DS-M: 14.9 ± 2.1 to 14.6 ± 2.5%). The absolute change in % body fat was similar between all groups (absolute Δ: $p = .729$; TRT: -0.2 ± 0.2%; DS-S: -0.1 ± 0.6%; DS-M: 0.3 ± 0.3%). Similarly, there was no significant interaction for SMM ($p = .694$). There was a significant main effect of time demonstrating an increase in muscle mass after 8 weeks of training ($p < .001$; $\eta^2 = 0.675$; TRT: 35.6 ± 3.5 to 36.7 ± 3.3 kg; DS-S: 36.2 ± 4.1 to 37.55 ± 3.9 kg; DS-M: 36 ± 3.7 to 37.47 ± 2.85 kg). The absolute change in SMM was similar between groups (absolute Δ: $p = .694$; TRT: 1.1 ± 0.8 kg; DS-S: 1.4 ± 0.9 kg; DS-M: 1.4 ± 1.1 kg).

Muscular strength and endurance

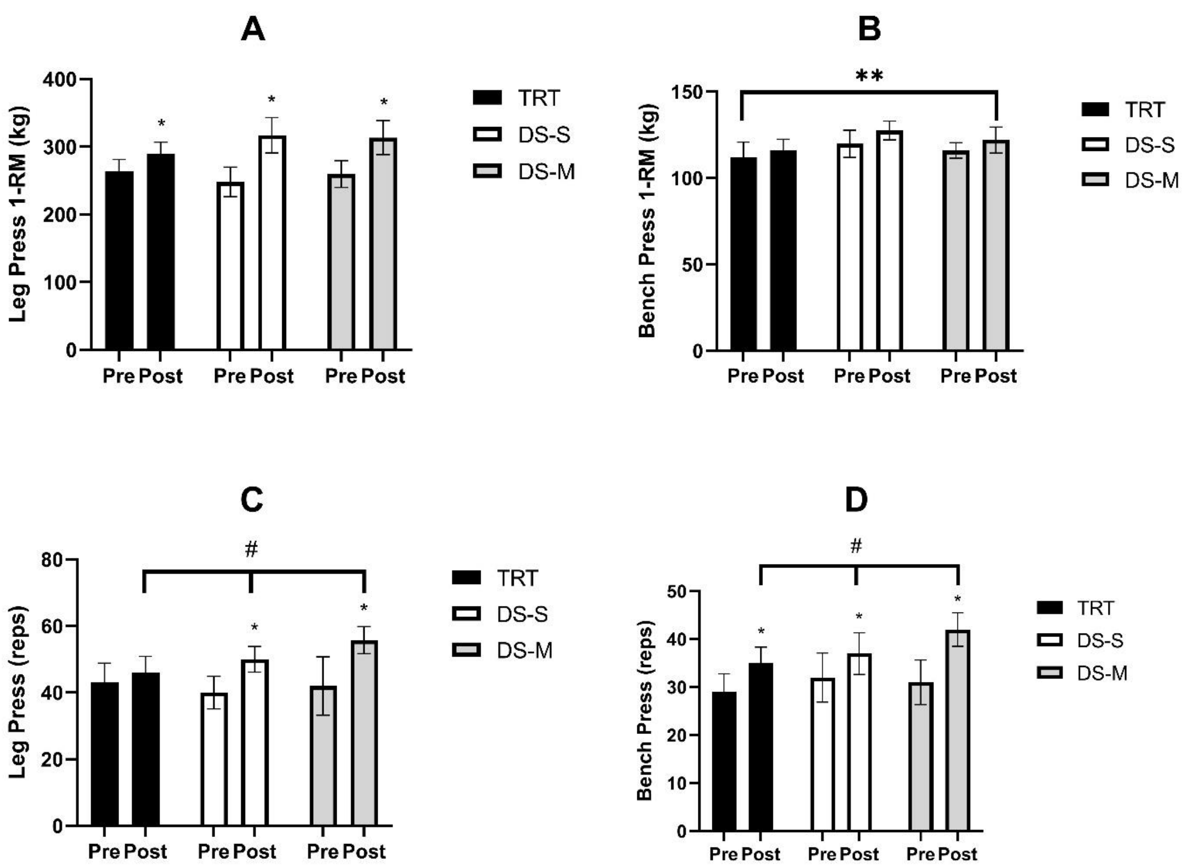
Isometric leg extension strength

There was no significant interaction for isometric MVC ($p = .579$), however there was a significant main effect of time ($p < .001$; $\eta^2 = 0.720$; TRT: 271.4 ± 15.8 to 279.6 ± 11.3 Nm; DS-S: 278 ± 20.5 to 286 ± 19.3 Nm;

DS-M: 280 ± 24.3 to 291.2 ± 18 Nm). The absolute change over time was similar between groups (absolute ∆: *p* = .579; TRT: 10.3 ± 8.9 Nm; DS-S: 7.9 ± 4.1 Nm; DS-M: 11.0 ± 5.3 Nm).

Leg press and bench press 1-RM

For leg press 1-RM there was a significant interaction ($p < .001$; $\eta^2 = 0.571$), as shown in figure 2A. Post hoc analysis revealed that all three groups increased over time (post > pre; $p < .001$), with no differences between post training values (TRT vs. DS-M, $p = .24$; DS-S vs. DS-M, $p = 1.00$; TRT vs. DS-S, $p = .10$); however, absolute change in leg press 1-RM values revealed a significant difference between groups (absolute ∆: $p < .001$; TRT: 26.5 ± 12.5 kg; DS-S: 69.0 ± 19.7 kg; DS-M: 53.9 ± 15.8 kg) with both DS groups increasing to a greater extent compared to TRT (DS-M vs. TRT, $p = .01$; DS-S vs. TRT, $p < .001$), with no differences between drop set groups ($p = .155$). For bench press 1-RM there was no significant interaction ($p = .541$), as shown in figure 2B, however there was a significant main effect of time ($p < .001$, $\eta^2 = 0.450$) demonstrating that post values were greater than pre training. Furthermore, there was no significant difference between groups for absolute change in bench press 1-RM (absolute ∆: $p = .183$; TRT: 4.1 ± 11.1 kg; DS-S: 7.7 ± 3.0 kg; DS-M: 6.1 ± 3.7 kg).



*Note. * = Significantly different than pre. ** = Main effect of time, # = Significant interaction.*

Figure 2. Pre post means and SD between groups for (A) leg press 1-RM, (B) bench press 1-RM, (C) leg press endurance, and (D) bench press endurance.

Leg press and bench press endurance

For leg press endurance there was a significant interaction ($p < .001$; $η^2 = 0.661$), as shown in figure 2C. Post hoc analysis revealed that the drop set groups increased over time ($p < .001$), while TRT did not ($p = .109$). Post training leg press endurance in the DS-M group was significantly greater than TRT ($p = .012$) but similar to DS-S ($p = .269$), while DS-S was not different than TRT ($p = .618$). The absolute change in leg press endurance was significantly different between groups (absolute Δ: $p < .001$; $η^2 = 0.661$; TRT: 3 ± 2 reps; DS-S: 10 ± 2 reps; DS-M: 14 ± 5 reps). Both drop set training protocols were superior to TRT ($p < .001$), with a trend for DS-M to be superior to DS-S ($p = .063$). For bench press endurance there was a significant interaction ($p < .001$; $η^2 = 0.699$), as shown in figure 2D. Post hoc analysis revealed that all groups increased over time ($p < .001$). In addition, post training bench press endurance values were significantly higher for DS-M compared to TRT ($p < .001$), however DS-S was similar to both TRT ($p = .901$) and DS-M ($p = .157$). Absolute change was significantly different between groups (absolute Δ: $p < .001$; TRT: 6 ± 2 reps; DS-S: 5 ± 2 reps; DS-M: 11 ± 2 reps). Post hoc analysis revealed that DS-M had a greater change than both DS-S and TRT ($p < .001$), while there were no differences between TRT and DS-S ($p = .45$).

DISCUSSION AND CONCLUSIONS

The purpose was to examine two different drop set protocols compared to traditional resistance training on muscular strength and endurance and body composition over 8-weeks (training 3 times per week) in trained participants. Specifically, the drop set protocols consisted of either a single-step or a multi-step reduction in load. The main findings were that both drop set protocols appeared to be superior to TRT to augment gains in lower body (leg press) muscular strength (however, caution is required since this was only noted for absolute change values and not within the post-hoc pairwise comparisons), however, only the multi-step drop set group was superior to TRT to enhance muscular endurance (both lower and upper body endurance), suggesting that variations in drop set protocols influences muscle adaptations and that performing multiple drops enhances muscular endurance without negatively impacting muscular strength comparing to a single reduction drop set training. Furthermore, there were no differences between training protocols with regards to body composition or upper body strength adaptations, but there was a significant main effect of time, suggesting that all three protocols similarly improved body composition and upper body strength over time. Resistance training adaptations are known to be influenced by intensity, duration, and training volume; however, the optimal training program remains to be elucidated (Brown et al., 2001; Schoenfeld et al., 2021). Gains in muscle hypertrophy and strength are associated with several factors, including metabolic and mechanical stress (Gligoroska et al., 2022). Drop set training is a form of training whereby participants rapidly reduce the load between sets which leads to large metabolic disturbances. Schoenfeld speculated that drop set training may elicit greater gains in hypertrophy due to the limited recovery time between sets thereby causing greater muscular fatigue and metabolic stress and Furthermore, drop set training increases time under tension and local hypoxia (ischemia), thereby creating a greater stimulus for muscle adaptations over time (Schoenfeld, 2013). Overall, resistance training is well-known to enhance gains in muscle mass (Kraemer et al., 2004). In the present study a main effect of time was observed for an increase in skeletal muscle mass (assessed via bioelectrical impedance), however, there were no difference between groups. Our results are in support of previous research comparing drops set training to traditional resistance training. For example, Enes et al. investigated 8 weeks of resistance training with either a drop-set training system or traditional resistance training or a rest-pause training system in trained males while They found similar improvements in lateral thigh muscle thickness (middle and proximal portions assessed with an ultrasound) between groups (main effect of time) (Enes et al., 2021). Interestingly, in the present study, there were no differences between traditional resistance training (4 sets of 10 at 75%) which was not performed to failure, while both drop set protocols were performed to failure. This suggests that training to failure is not required to increase muscle gains over time. Furthermore, in the previous study, a greater increase in back squat 1-RM was found in the rest-pause group, but similar increases were noted between the drop set training and the traditional resistance training groups. These results partially support our findings (Enes et al., 2021; Prestes et al 2019). Our results found a significant interaction for leg press 1-RM; however, the pairwise post hoc comparison revealed no differences between groups. However, absolute change (post values minus pre values) was significantly greater for both drop set groups compared to TRT, which suggests a greater change over time for drop set training induced gains in lower body strength. In contrast, Fink et al. reported that after 6 weeks of resistance training with drop set training compared to traditional resistance training, there were similar increases in muscle strength and muscle cross sectional area (Fink et al., 2018). With regards to changes in muscular endurance, our results revealed that the DS-M group had greater improvements following training compared to DS-S or TRT. These differences may be associated with greater alterations in metabolic disturbances and mechanical stress (Brown et al 2001; Ozaki et al 2016; Wackerhage et al 2019). Our findings are in support of previous research, for example, Recio et al. reported that a drop set protocol increased muscle endurance of the trunk extensor muscles of trained males (n = 30) assessed during a deadlift movement following 6-weeks of resistance training. From the results of their research in conjunction with our findings, it may be concluded that the multi-step drop set protocol enhances muscle endurance to a greater extent than single step reduction drops set protocol or traditional resistance training (Recio et al., 2018). Future research is required to explore mechanisms that may explain these findings, however, they are likely due to the greater metabolic stress. Ozaki et al. found that drop-set resistance training was an effective strategy to simultaneously increase muscle CSA, strength, and endurance in untrained young males, even with lower training time compared to traditional resistance exercise protocols using only high- or low-loads (Ozaki et al., 2018). However, the present study failed to find robust increases in strength and body composition changes relative to traditional resistance training, possibly due to investigating males with resistance training experience whereas Ozaki investigated untrained participants.

This study is not without limitations. Despite drop-set training appearing to be superior to TRT for gains in lower body strength, and multi-step drop set training being superior to TRT for muscle endurance, it is important to note that TRT was not performed to failure. Importantly, there was no differences between DS-S and TRT for muscle endurance and bench press 1-RM, suggesting that despite this limitation (i.e. one group training to failure and the other not), there were no differences found between these two groups. Overall, these suggest that the greater gains in muscle performance observed in the multi-step group are more likely due to other factors (such as metabolic stress). Another limitation of this study was the lack of mechanistic data, and future research exploring mechanisms are warranted. In addition, we only examined whole-body changes in skeletal muscle mass and percent body fat. in this regard, a study has found regional differences in muscle thickness changes with drop-set changes (Wackerhage et al., 2019). Lastly, future research in females is required to examine sex-based differences.

Practical application

Based on our findings, single-step and multi-step drop-set training to failure appear to be effective strategies to enhance lower body strength, while only the multi-step drop-set training protocol enhanced muscular endurance compared to TRT. All three training protocols were equally effective at improving body composition. Future research is required to explore mechanisms and potential sex-based differences in response to drop-set training protocols.

AUTHOR CONTRIBUTIONS

Conceptualization, M. F., M. B., B. D. and M. N.; research concept and study design, M. B. and B. D.; data collection, M. F.; data analysis and interpretation, M. T., M. F., M. N., and S. C. F.; writing of the manuscript, M. T. and M. F.; editing a draft of the manuscript, J. G-L. and S. C.F.; writing—review and editing, M. N., M. F., J. G-L. and S. C.F. All authors have read and agreed to the published version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS STATEMENT

The study was approved by an Institutional Ethics Review Board at the Shahid Beheshti University of Tehran (IR.SBU.REC.1400.161).

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study.

DATA AVAILABILITY STATEMENT

The data are available if there is justified research interest.

ACKNOWLEDGMENTS

The authors thank the volunteers' engagement during research conduction.

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SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

Application and prospect of new media in sports news dissemination

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ABSTRACT

In the process of the rapid development of Internet technology, new media has been maturing with the development of information technology, providing a new way for information dissemination. The media promotes sports and draws people's attention to them. In this research, the same topic was revealed with documentary data, the qualitative method was used to clarify the topic, and all the accurate information that was published in reliable books, scientific magazines, and internet sites was collected. The application of new media in the process of sports news dissemination requires research and analysis of the application and development of new media, which is conducive to mastering the application of new media in sports news, understanding the development trend of new media, and giving full play to sports news. spread effect. Research findings suggest that new media has revolutionized the way sports news is disseminated and consumed. With the rise of social media platforms, sports fans now have access to instant updates and analysis from a variety of sources, including traditional news outlets, blogs, and social media influencers. The application of new media in sports news dissemination has led to increased engagement between sports fans, athletes, teams, and media outlets. Social media platforms such as Twitter, Instagram, and Facebook allow for real-time communication and interaction between these groups, creating a more immersive and interactive experience for fans. The prospects for new media in sports news dissemination are tremendous, with continued advancements in technology and the increasing popularity of social media platforms. Overall, the research suggests that the application of new media in sports news dissemination has had a significant impact on the industry, and the prospects for future growth and innovation through new media channels are bright.
Keywords: New media, Sports news dissemination, Application analysis, Development prospect.

Cite this article as:
Bahir, H., Abed, S. A., & Ziarmal, M. R. (2023). Application and prospect of new media in sports news dissemination. *Scientific Journal of Sport and Performance*, *2*(3), 423-427. https://doi.org/10.55860/YIQV1201

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Submitted for publication June 07, 2023.
Accepted for publication June 15, 2023.
Published June 20, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/YIQV1201

INTRODUCTION

New media is constantly changing. To define new media technically, it can be defined as a new type of media that provides information to the audience. New media includes mobile communication, Internet, and new TV technology. Therefore, in the process of applying various technologies, the channels and methods of media information dissemination are relatively rich, and no longer rely solely on traditional newspapers, radio, television and other media for information dissemination. Compared with traditional media, the biggest advantage of new media is that information spreads quickly, spreads widely, is not limited by time and space, and has a huge amount of information resources. In addition, in the process of new media information dissemination, the roles between the audience and the communicator are not fixed, which is also a prominent feature of new media in information dissemination (Xu et al., 2023). Application and significance of new media in sports news dissemination in the process of the rapid development of new media technology, it is of great significance to apply it to sports news dissemination, mainly in the following aspects: First, a cross-media information delivery platform can be constructed (Rouhi Dehkordi, 2017). In recent years, the rapid development of social media has provided a good platform for the public to participate in news dissemination. When reporting sports news, new media can cooperate with traditional media to build a cross-media communication platform. When new media cooperates with traditional media, it can effectively innovate the content and form of communication in a very short period of time, continuously stimulate the vitality of new media in the process of sports news dissemination and satisfy the audience's expectations to the greatest extent. information content needs. Second, it can improve the objectivity and authenticity of sports news. At present, in the process of sports news dissemination, the framework of new media is relatively mature and perfect, and media workers should fully integrate the advantages of traditional media according to the application value of different media types. At the same time, it is necessary to give full play to the application advantages of new media technology and improve the quality of sports news dissemination (Bellamy, 2009). In order to achieve this goal, when new media disseminate sports news, they need to learn from traditional media and pay attention to the depth of sports news content so as to reflect the spiritual needs and value of sports news. In addition, it is necessary to comprehensively analyse and summarize the laws, results, and turning point data of sports events. In this way, the application value of sports news dissemination can be further enhanced. Third, we can tap into and utilize the technological advantages of new media. New media itself is a new type of media developed on the basis of network technology, information technology, and digital technology (Bird et al., 2013). When disseminating sports news, it is necessary to give full play to the application advantages of these advanced technologies and deeply integrate new media technology with sports news dissemination. This requires the continuous development and application of new media technology in order to provide effective and reliable technical support for sports news dissemination. At the same time, it is also necessary to make full use of the current carriers, such as digital TV, Internet TV, and mobile TV, and continuously expand the channels of new media for disseminating sports news (Pilar et al., 2019). Fourth, it is conducive to enhancing the interaction and communication levels of the public when receiving sports news. In order to give full play to the interactive advantages of new media in the process of sports news dissemination, it is necessary to build a platform for social public interaction and communication. Especially in the era of mobile Internet, the roles between the audience and the communicator are highly transformable (Yuldashev, 2021). Whether it is a professional reporter or an ordinary audience, they can use new media to complete the sports news dissemination process. In response to this situation, it is necessary to give full play to the advantages of the new media as a communication platform to prevent the dissemination of false news information during the dissemination process and affect the positive role of the new media in the dissemination of sports news. For example, in the Rio Olympics, the Olympic official website used new media to interact and communicate with the audience in real time. Both Chinese and foreign mainstream media have made full use of the website to launch the Olympic Channel and set up a variety of interactive sections, which is of great help in expanding the influence of the Olympic Games and deepening their significance (Nataliia et al., 2019).

Research's significance

Research plays a critical role in the development of new media technologies and their application in sports news dissemination. By analysing audience preferences, understanding emerging technologies, and keeping up to date with industry trends, researchers can help sports media organizations stay ahead of the curve and deliver content that resonates with their target audience. New media technologies such as social media, mobile apps, live streaming, and virtual reality have transformed the way sports news is disseminated. These technologies offer new opportunities for sports media organizations to engage with their audiences, increase brand awareness, and generate revenue streams. The prospect of new media in sports news dissemination is vast, with the potential to revolutionize the way sports fans consume and interact with their favourite sports. For instance, social media platforms like Twitter, Facebook, and Instagram allow fans to connect with their favourite athletes and teams, share their opinions, and receive breaking news in real-time. Mobile apps and live streaming services enable fans to access sports content on-the-go and watch games from anywhere in the world. Virtual reality technology provides a fully immersive experience, allowing fans to feel like they are part of the action and attend sporting events remotely. In conclusion, the application of new media technologies in sports news dissemination offers significant benefits to sports media organizations and fans alike. By embracing these technologies and conducting ongoing research into emerging trends, sports media organizations can enhance their engagement with audiences, increase revenues, and stay competitive in an ever-evolving landscape.

PRACTICAL APPLICATION OF NEW MEDIA IN SPORTS NEWS DISSEMINATION

Provide a communication platform for sports fans

In the process of continuous application and development of new media technology, it can provide audiences with a platform to choose news content according to their own needs and greatly mobilize the enthusiasm of sports fans to pay attention to sports news. On the communication and interaction platform, the audience can express their own opinions based on the received sports news (Chen, 2018). In addition, the sports news disseminated on the interactive platform is not restricted by region or time. Therefore, the audience can communicate and express their opinions on the content of sports news at any time. This method can enhance the breadth and depth of sports news dissemination and reflect a strong feedback effect.

Publicity and promotion of sports events

In the information age, we must give full play to the value of information in order to use it to obtain economic benefits. The process of sports news dissemination, especially the effective publicity and promotion of some major events before they are held, is an important measure to increase the attention of sports events. At present, when new media publicize and promote sports news, they can use Weibo, professional websites, WeChat public accounts, etc. to achieve the purpose of publicity and promotion (Hughes & Shank, 2005). This kind of publicity and promotion can lay a good audience base for the broadcast and live broadcast of sports events and is conducive to expanding the influence of sports events. Before the start of sports events, users can collect and find information related to sports events on the Internet and learn about the event arrangements in advance, which is of positive significance in promoting the dissemination of sports news. For example, before the start of the Guangzhou Marathon, in order to achieve the purpose of promoting the event, the operator directly released the appointment running app to the market. This product can not only record and track the user's running exercise and running route but also introduce the marathon. And various functions, such as competition pre-registration, can increase the popularity of the event to a large extent and increase the audience's participation in the event (Gumantan et al., 2021).

Broadcast and live sports events

The application of new media in the process of sports news dissemination has great advantages; for example, sports events can be rebroadcast or live broadcast. Since the successful hosting of the Beijing Olympic Games, the attention of Chinese people to various sports events has been increasing, which has laid a good audience foundation for the application of new media in the live broadcast and broadcast of sports events. When live broadcasting and rebroadcasting sports news, it can be divided into text broadcasting and video broadcasting according to the difference in communication media. The live text broadcasting appeared earlier, while the live video broadcasting appeared relatively late (Rowe & Gilmour, 2010). Before the application of new media to the dissemination of sports news, live text and live video coexisted. However, with the rapid development of new media technology, live video has become one of the main modes of broadcasting, including live broadcasting of sports news. As early as 2015, my country's Internet giant Tencent signed a contract with the NBA to sell the copyright of NBA sports events to Tencent, opening a new era of live broadcast of sports events in my country. The timeliness of using new media to broadcast sports events is relatively strong, and it can bring audiences the exciting feeling of major sports events in fierce confrontation, which is the main advantage of live video broadcasting. Especially in the process of continuous development of online video live broadcast, viewers can use the live broadcast platform to communicate and enhance the audience's interactivity and pleasure.

The development prospects of new media in the application of sports news dissemination

At present, the application of new media in the process of sports news dissemination is relatively extensive, and with the further development of new media technology and its in-depth application in the process of sports news dissemination, new media forms and means will be used in the process of sports news dissemination. Great changes occurred. Especially with the development of mobile terminal technology, the application of new media in sports news dissemination in the future will be more inclined toward mobile terminals, which will become an important carrier for people to receive sports news. In addition, public transportation will also become one of the main application scenarios for new media in the dissemination of sports news. For example, on public transportation such as subways, buses, taxis, and high-speed trains, some promotional posters can be used to promote sports events.

CONCLUSION

The application of new media in sports news dissemination can greatly enhance the breadth and depth of sports news dissemination, broaden the channels of sports news dissemination, meet the audience's various demands for sports news, and enhance the interactivity and openness of sports news dissemination. However, there are also some problems when using new media to disseminate sports news. For example, some false information spreads faster, which may mislead the audience. Therefore, it is necessary to fully explore the development model of new media in the process of sports news dissemination, give full play to the positive role of new media in news dissemination, and promote the prosperity and development of sports news dissemination.

AUTHOR CONTRIBUTIONS

Hizbullah Bahir: literature review, research method and design, research analysis, and generally completed most of this research. Sayed Anwershah Abed collected the primary data and presented a general idea about the research. Mujeeb Rahman Ziarmal edited the complete article, completed the research principles and completed the grammar section.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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